Northumbria University NEWCASTLE

2019

18–20 September

Advances in ICT in Design, Construction &Management in Architecture, Engineering, Construction and Operations (AECO)

Proceedings of the 36th CIB W78 2019 Conference

Edited By:
Bimal Kumar
Farzad Pour Rahimian
David Greenwood
Timo Hartmann

Northumbria University
Newcastle
United Kingdom

Advances in ICT in Design, Construction and Management in Architecture, Engineering, Construction and Operations (AECO)

Proceedings of the 36th CIB W78 2019 Conference

Editors

Bimal Kumar
Northumbria University
Newcastle, UK

Farzad Rahimian
Teesside University
Middleborough, UK

David Greenwood
Northumbria University
Newcastle, UK

Timo Hartmann
Tu Berlin
Berlin, Germany

Layout Editor

Moslem Sheikhkhoshkar
Teesside University
Middleborough, UK

ISBN (Print) 9781861354877

ISBN (eBook) 9781861354860

Preface

The CIB – International Council for Research and Innovation in Building Construction – was established in 1953 as an association whose objectives were to stimulate and facilitate international cooperation and information exchange between governmental research institutes in the building and construction sector, with an emphasis on those institutes engaged in technical fields of research. The CIB is organized in working groups, of which the W78 is responsible for IT in construction.

This volume is a collection of papers presented at the 36th Annual Conference of the CIB W78 work group held at Northumbria University in Newcastle, UK in September (18th-20th), 2019. The conference brings together more than 130 scholars from over 30 countries, representing research undertaken all over the world.

The papers embody state-of-the-art in research on digitalisation in built environment and encompass major topics including IoT, Digital Twins, Cyber-Physical Systems, Building Information Modelling. As such this volume serves as a source of reference for researchers in ICT applications in design, construction, operation and maintenance for the Architecture, Engineering, Construction and Operation industries across the world.

Newcastle, UK
September 2019

Prof Bimal Kumar
Dr Farzad Rahimian
Prof David Greenwood
Prof Timo Hartmann

Contents

Part 1. Artificial Intelligence & Digital Construction

Part 2. BIM and Lean Construction

Part 3. Blockchain & Cyber-Physical Systems

Part 4. Building Information Modelling

Part 7. Engineering Design & Collaboration Technologies

Part 8. Integrated Process & Automated Approaches

Part 9. Situation Awareness and Sensing Technologies

Artificial Intelligence & Digital Construction

Capabilities needed in Information management for a Digital Built Britain

Peter Demian[1, *], Steven Yeomans[1], Danny Murguia[1], Matthew West[2], Mohamad Kassem[3], Hadeel Saadoon[4] and Paul Turney[5]

[1]Loughborough University

[2]Information Junction

[3]Northumbria University

[4]Coventry University

[5]Network Rail

*email: P.Demian@lboro.ac.uk

Abstract

Network FOuNTAIN is the Network For ONTologies And Information maNagement in Digital Built Britain, a project funded by the Centre for Digital Built Britain. The vision of the Network is for all stakeholders in Digital Built Britain (DBB) to be able to meet their information needs. With the establishment of concepts such as Building Information Modelling and Common Data Environments, built environment design, construction and operation are becoming increasingly information-intensive. The Network undertook five workshop activities between July and December 2018. This paper summarises the proceedings of these workshops, and in particular establishes future capabilities needed to realise the vision of DBB. The first workshop sought to establish the scope of "Information Management". It was concluded that the capability to gauge Information Management Maturity was needed. The second and third workshops focused on ontologies and reviewed the variety of standards currently available. It was concluded that the capability was needed to establish the appropriate scope of standardisation, and to design or extend existing ontologies in general. The capability was also needed to develop current classification systems, schema and frameworks, Uniclass 2015 in particular, to maximise the potential to share data. The fourth workshop explored system requirements; it identified three modes of consuming information and the corresponding software requirements for each mode. The three modes identified are: *Search & Retrieval*, *Browsing & Expiration* and *Information Delivery*. The fifth and final workshop focused on business models and concluded that the capability was needed to identify and derive business value from Information Management. The paper closes with a research agenda required to deliver those capabilities. Fundamental research is needed to formulate a process of establishing the appropriate scope of standardisation for Information Management at *project*, *organisation* and *industry* levels. This research needs to unfold in the context of emerging related international standards.

Keywords: Information Management, Ontologies, Capabilities

1. Introduction

Information is a crucial component of any perspective of Digital Built Britain (CDBB 2018a). Information can flow from the users and other stakeholders of the built environment, including those associated with services that depend on the built environment, back to the professionals who plan, design, build and operate built assets. The effective generation and exchange of information during this whole life cycle of built assets enable an improved delivery of the built environment. For example, users of the built environment and of services (and the providers of those services) can use information generated by built environment professionals for more effective operation of the built environment and provision of services. The Hackitt report (2018), presented to Government in the wake of the Grenfell Tower fire that killed 72 people, calls for a "golden thread" of good quality information to enable building owners to better manage their buildings safely. The information flows within the design and construction teams of constructed facilities are particularly important in the effective provision of the built environment.

The complex nature of projects coupled with the diversity of the delivery team gives rise to the need for standards and ontologies as part of an Information Management strategy. Information Management has been proposed as an important component of roadmap to DBB (Enzer et al. 2019). As a predecessor to that roadmap, and posed more broadly than merely constructed infrastructure, better data has been proposed as the enabler for citizens to make better decisions (NIC 2017).

This paper describes the work of the Network For ONTologies And Information maNagement (Network FOuNTAIN) to determine the *capabilities in Information Management* needed in a Digital Built Britain (DBB). The Network was supported by the Centre for Digital Built Britain and comprises researchers and industry practitioners. The vision of the Network is for all stakeholders in DBB to be able to meet their information needs, with access to the information they need about the built environment as they work to deliver and operates buildings and infrastructure. With the establishment of concepts such as Building Information Modelling (BIM) and Common Data Environments (CDE), built environment design, construction and operation are becoming increasingly information-intensive.

The Network undertook five workshop activities between July and December 2018. The purpose of those workshops was to:

(0) Scope out the issue of Information Management in DBB;

(1) Explore ontologies to extract information from data;

(2) Catalogue the types of information to be managed in DBB;

(3) Specify software requirements for tools to manage this information; and

(4) Investigate an approach to formulate a process model for delivering value from Information Management.

This paper presents the outcome of those activities listed above and attempts to extract the capabilities required by stakeholders to deliver a Digital Built Britain. The full report from the Network has been published (Demian et. al 2019).

2. Methodology

The work of the Network was undertaken by convening workshops, as listed above. The workshops broadly included introductory presentations followed by unstructured discussion sessions. The workshops were audio-recorded to ease notetaking, and the recordings were destroyed immediately after a report was circulated and approved by attendees following each workshop. The ordering of the workshops was intended to follow a logical sequence: Workshop 0 scoping the topic, Workshop 1 focusing on the creation of information through ontologies, Workshop 2 cataloguing the types of information to be managed, working 3 investigating the software functionality needed, and Workshop 4 exploring the process of deriving business value. The only exception to the standard workshop method was for Workshop 2, as described in section 5.1.

3. Scope of Information Management

The first workshop, Workshop 0, focused on the scope of Information Management, and attempted to establish a theoretical lens through which the subsequent work of the Network could be managed. It was led by Mr Matthew West and was attended by nine individuals: four academics and five industry practitioners. From the workshops discussion, it was noted that the value of information comes from its use in supporting decisions. *Information Management* is about ensuring the right information is delivered at the right time to the right people. *Quality* means meeting requirements agreed between information users and suppliers.

3.1 Information Management Landscape (IML)

The Information Management Landscape (IML) found in a White Paper by West and Cook (2018) was discussed at the workshop and informed subsequent activities. That publication uses examples to illustrate the capability required for data integration and identifies the elements of the IML required to deliver that capability, as shown in Figure 1.

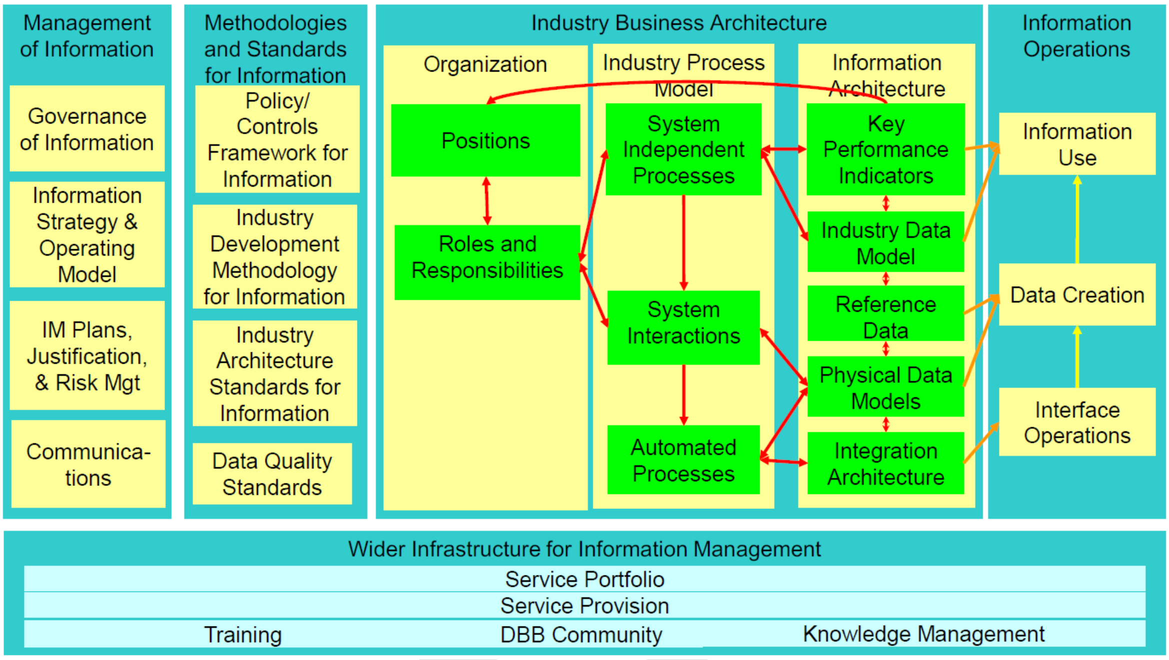


Figure 1: The Information Management Landscape, (reproduced from West and Cook 2018)

The IML proved to be a useful guide for planning and managing the subsequent activities of the Network. Workshop 1 on Ontologies and Workshop 2 on Cataloguing Information both addressed the "Industry Architecture Standards for Information" element. Workshop 3 on System Requirements addressed the "Information Use" element. Workshop 4 on Business Models addressed the entire "Industry Process Model" block.

ISO19650 Part 1 (ISO 2018a) provides an alternative representation of the Information Management domain specifically for the built environment. It refers to the purpose of information, and defines trigger events and key decision points where an information requirement might arise.

3.2 Information Management Maturity

IM Maturity can be broken down into five stages: *Initial*, *Recognising*, *Specifying*, *Managing* and

Optimising (West 2011). Workshop attendees discussed the maturity of the industry as a whole, and of particular groups or organisations. At the publication of the Latham Report in 1994, the industry was considered to be still at the *Initial* stage. The Avanti project around 2006 (Constructing Excellence 2006) perhaps signalled *Recognising* maturity. The release of COBie and the emergence of the concept of Open BIM signal important milestones in UK industry Information Management maturity, but formal classifications are difficult.

No clear consensus was reached regarding IM maturity of companies. Attendees agreed that the client is the most important "organisation" to drive maturity, pushing the IM agenda or pulling the information it needs. Generally, it was felt that many organisations are at *Specifying* level.

ISO19650 Part 1 (ISO 2018a) gives an alternative classification of IM maturity, (again specifically for the built environment, or the adoption of BIM) broken down into three Stages, which supersedes the BIM Levels of the classic Bew-Richards "wedge" (CIOB 2018).

Capability 0: Capability to gauge Information Management maturity, as part of existing standards or new standards.

3.3 Current Information Management Research

As an indicative "snapshot" of current IM research, attendees of Workshop 0 were asked to map their research activities against the elements of the IML. The nested nature of the IML elements prevented meaningful identification of research gaps. It appeared that the "Industry Data Model" element is receiving much research interest, with other items being the focus of some research activity. The work of Network FOuNTAIN, and particularly of Workshop 2, add to this. As a snapshot of the research gaps in the work of attendees' organisations in August 2018, the following elements had no research activities mapped to them:

- Management of Information
- IM Plans, Justification, & Risk Management
- Communications
- Policy, Controls Framework for Information
- Industry Development Methodology for Information
- Industry Architecture Standards for Information
- Industry Business Architecture
- Positions
- Information Architecture
- Key Performance Indicators
- Physical Data Models
- Integration Architecture

4. Ontologies

Workshop 1 was led by Professor Stuart Barr of Newcastle University and Dr Tom Beach from Cardiff University. It was attended by seven academics and nine industry practitioners, including two industrial advisors or consultants to the UK Government. An "Ontology Tutorial" was presented, followed by a session where several attendees presented case studies of how ontologies were used in their professional practice. The workshop closed with a discussion of the current industrial and academic use of ontologies, gaps in the state-of-the-art and opportunities for future development.

4.1 Fundamentals of Ontologies

Ontologies are a formal, standard representation of objects, their attributes and relationships between them. This representation is often used for reasoning. *Schemas* are similar to ontologies, but are often created for the purpose of designing database systems, and so their emphasis is on storing and querying datasets, rather than reasoning. *Standardisation* is an inherent characteristic of ontologies.

The main theme that emerged from that part of the workshop is *the tension between standardisation and flexibility*. A balanced approach is to standardise common aspects and allow users to extend bespoke aspects. Too little standardisation means high flexibility for all stakeholders but can result in poor interoperability between stakeholders (no common language). Too much standardisation results in inflexibility and risks stakeholders not using the ontology. The balance can be expressed in terms of "standardising the right things", rather than too much or too little standardisation. This is set out in Capability 1a below. It is noteworthy that Uniclass 2015 was identified as having a significant following and value to the practitioner community. Like several of the standards cited at that workshop, Uniclass 2015 can be argued to be a classification system rather than an ontology in the strictest sense. In some applications, the ISO15926 series of standards has been found to offer more flexibility than Uniclass 2015 in terms of object attributes (BIM4Water 2017). Uniclass 2015 has been restructured and redeveloped to provide a comprehensive system suitable for use by the entire construction industry and for all stages in a project life cycle (NBS 2018a). Despite aspects of extensibility, the fact that objects could only be classified in a single way in Uniclass was considered a weakness. It is important that any approach to ontology development give due consideration to valued current tools, for example Uniclass 2015, exploring ways to integrate available insights and best use current investments and skills.

Capability 1a: Capability to establish the appropriate scope, priorities and pace of standardisation, at *industry*, *project* and *organisation* levels.

4.2 Ontological Issues Faced by the Industry

In addition to the issue of standardisation vs. flexibility outlined above, the following issues emerged from the discussion:

- "Principles" need to be established at the outset, before designing or adopting an ontology. What are the needs and purposes of information creators, managers, users?
- Clarity is needed regarding the nature of existing standards. Are they ontologies (ifcOWL), schemas (IFC, CityGML), or classification systems (Uniclass 2015, COBie) and therefore what might be their role in the future?
- What are the strengths and weaknesses of candidate ontologies? [This issue was addressed in the subsequent Workshop 2.]
- What is the appropriate scope of an ontology: buildings, cities, infrastructure, linear infrastructure? Is it required or reasonable for a single ontology to cover all? [This issue overlaps with the issue of standardisation vs. flexibility and is addressed in Capability 1a.]

The discussion from that part of Workshop 1 can be distilled in Capability 1b:

Capability 1b: Capability to underpin data exchange and integration by developing an appropriate approach to develop new, to extend and adapt existing ontologies, and to create the means to integrate current schema and classifications. (A prescriptive process model is needed.)

5. Ontologies for Cataloguing Information

The original aim of Workshop 2 was to create a list (or catalogue) of all the various types of information that require managing in DBB. However, following a number of informative discussions at the earlier workshops, it became apparent that such listing might already exist in existing ontologies or standards. Instead, a panel of expert practitioners was surveyed to review current ontologies and standards, to investigate how they categorise information. The Delphi method was used through an online platform. Like Workshop 1 before it, the focus of Workshop 2 corresponds to the "Industry Architecture Standards for Information" element of the IML, and perhaps touches on the "Information Operations" element.

5.1 Method

An initial desktop literature review was conducted to identify current ontologies or standards for Information Management in the built environment, a catalogue of information types, and a list of project processes within the current standards. The Delphi method was then applied in an attempt to achieve a reliable consensus from the panel of experts over two initial rounds of enquiry. Practitioners from the Network were invited to form the panel of experts. A third round was included to capture additional comments from the experts, as well as substantiate experts' key credentials. A summary of the results from the previous round was used to inform consensus building in the subsequent round. Participants were encouraged to review the anonymous opinions of all experts, before being provided with an opportunity to revise their previous response, thus supporting a more consensus-based conclusion.

The questionnaire contained four key sections:

- Section 1: enquired about the *suitability*, *completeness*, and *adaptability* of current ontologies or standards, i.e. IFC, Uniclass 2015, COBie, CI/SfB and CityGML. Questions were assessed using a Likert Scale from 1 to 5.
- Section 2: interrogated participants about the possibility of combining ontologies to obtain a more comprehensive information catalogue.
- Section 3: asked the experts to define what are the most important types of information. Open-ended questions were then used to explore future trends in types of information.
- Section 4: enquired about the *suitability*, *completeness*, and *adaptability* of current process models, namely, Construction Industry Council (CIC) Scope of Services, RIBA Plan of Work 2013, PAS1192:2 and the Government Soft Landings (GSL), again using a 1-5 Likert Scale.

5.2 Findings

Experts could not reach full consensus on one particular ontology or standard generally being the most suitable. However, Uniclass2015 did stand out as having a significant following. Similarly, for the project processes, none attained the scores required for consensus to be decisively considered the most *suitable*, *complete*, and *adaptable*. However, the project processes of PAS1192:2 generally emerged as the most suitable and adaptable.

Table 1: The Most Important Information Types for a Digital Built Britain (in ranked order)

Importance of Information Types	Rank	Second Round Results		
		Mean	Median	STDEV
Asset information	1	4.5	4.5	0.50
Record information (certificate, forms, manual, plan, register, report)	2	4.00	4.00	0.71
Data set (GIS dataset, information exchange file, room data sheet)	3	4.00	4.00	1.00
Graphical (drawing, 2D models, 3D models, photograph)	4	3.63	4.00	1.11
Design information (calculation, schedule, specification)	5	3.50	3.50	0.87
Contractual (client requirement, contract, instruction)	6	3.38	3.00	0.70
Financial (bills of quantity, cost plan, invoice)	7	3.00	3.00	0.71
Planning control (consent)	8	2.88	3.00	1.05
Project planning (method statement, policy, procedure, programme)	9	2.63	2.50	0.99
Communication (brochure)	10	2.63	2.50	1.32
Communication (request for information, technical query)	11	2.50	2.50	1.12
Communication (correspondence, file note, memo)	12	2.13	2.50	0.93
Record information (snagging list, survey, transmittal)	13	2.63	2.00	0.86

The experts' opinions were also collected on what are the most important information types to be managed. The Government Soft Landings (Cabinet Office, 2013) information categories were initially used. The GSL categories all refer to “Government department assets”. Despite this, experts from the first round felt that “Asset information” should be added as a separate category, which was subsequently scored highly by the experts. The initial results are presented in Table 1. “Asset information” was ranked top, with “Record information” and “Data set” ranked second and third respectively. Thorough analysis of these data will be reported in future publications.

As for Workshop 1, the initial findings from Workshop 2 point to Uniclass 2015 as having significant (but not consensus) support, providing coverage of many of the needs of a candidate standard framework to share data. Capability 2 can preliminarily be set out as follows:

> Capability 2: Capability to develop current classification systems, schema and frameworks, Uniclass 2015 in particular, to maximise the potential to share data, best using current skills and investments.

6. System Requirements

The purpose of Workshop 3 was to explore the requirements in BIM and CDE platforms, focusing on the *consumption* (as opposed to the *production*) of information. This focus corresponds to the “Information Use” element of the IML. The Workshop was led by Peter Demian, and was attended by four academics, six construction delivery practitioners and one construction IT practitioner.

Three modes of interaction were presented: (1) Search & Retrieval; (2) Browsing & Exploration; and (3) Information Delivery. The choice between the three modes depends on the task at hand, the type of content (information) being managed and (most importantly) the user’s awareness of his or her information need. If the user knows exactly what information is needed, he or she will be able to articulate a query, search and retrieve the required information. If the user is unsure exactly what information is needed, but has some notion of an information need, browsing and exploration might be more appropriate. If the user has no idea what information is needed, or is even unaware that there is a need for information or that useful content might be available, the system unilaterally delivering information to the user might be the most effective mode of interaction.

6.1 Search & Retrieval

Search & Retrieval is appropriate when the user is aware of the information need with some precision, and the nature and sheer scale of the information make it difficult to visualise the whole repository and explore it systematically. The example of the 3DIR project was presented at Workshop 3 (Demian et al. 2016). The task of formulating queries in Search & Retrieval received particular attention in the workshop discussion. Queries in a natural language would be extremely useful, as would query templates or a visual query language (akin to visual computer programming).

6.2 Browsing & Exploration

Browsing & Exploration is useful when the awareness of the information need is not precise enough to enable formulation of an explicit query. It might also be more effective when interacting with a moderately sized (rather than large) repository of information. Even though no explicit query is formulated, some data from the user’s current task can be extracted and used as an *implicit query*, to highlight potentially relevant items in the repository. The “Shneiderman mantra” of “overview first, zoom and filter, and then details on demand” was cited (Shneiderman 1996). The CoMem project was presented as an example of this mode of interaction (Fruchter and Demian 2002).

From the discussion, Uniclass 2015 again emerged, this time as the most likely representation of practitioners’ search models to structure Browsing & Exploration. The relative simplicity and hierarchical nature of Uniclass 2015 were both seen as beneficial characteristics. Its limitations include its inflexibility and its poor coverage of infrastructure information.

6.3 Information Delivery

If a user has no idea what information is needed, or is unaware that useful content might be available, the system can unilaterally deliver information which might be deemed relevant based on an implicit query from the user's current work. In DBB, particular protocols require that information is delivered to particular stakeholders at particular times (for example, CDE Sub Group 2018), and this is a possible application of this mode. It was agreed that Information Delivery, sometimes considered disruptive, *did* have a place in CDE ad BIM platforms.

6.4 Software Requirements and Capabilities

The aim of Workshop 3 was to establish the software requirements for Information Management functionality in BIM and CDE platforms. The following functionality can be distilled from the discussion:

- Querying repositories using a visual syntax or the natural language used by stakeholders
- Browsing & Exploration of information repositories based on Uniclass 2015
- Information Delivery based on industry or project protocols

These functions can be framed as the following capability required by UK software developers:

Capability 3: The capability to develop fit-for-purpose software which enables stakeholders
-to query information repositories visually or using natural language,
-to explore information repositories based on current models (such as Uniclass-2015),
-to interrogate information repositories automatically using ontology-based tools, and
-to set information delivery schedules based on industry and project protocols.

The three modes of information consumption and the corresponding capabilities should enable the effective *finding* and *understanding* of information. These complement the Plain Language Question (PLQ) approach (NBS 2018b), whereby a client or employer poses questions at various decision points or construction stages. The NBS BIM Toolkit (NBS 2018c) includes a function for drafting PLQs and allocating them to project stages and appointments. The BIM Task Group gives a set of PLQs categorised across the project stages (BIM Task Group 2018). PLQs can be used as the mechanism to query or browse repositories, or drive the creation and delivery of information.

7. Business Models

Mohamad Kassem from Northumbria University led a discussion of business process models and made a case for a value-driven ontology for business models under DBB, sttended by five industry practitioners and five academics. This focus aligns with the "Industry Process Model" block of the Information Management Landscape (Figure 1).

There was consensus that a systematic approach is needed for identifying and delivering business value (in broader terms, including social, economic and environmental value) from Information Management. The use cases explored by the attendees (the use of digital data to improve service delivery in healthcare infrastructure, and the use of digital data to improve the use orperformance of equipment on site) highlighted the challenges of understanding how value can be created from managing digital data. There is a need for a systematic method to explore the value chain involved in creating and exchanging digital data to unlock business value. The merits of ontologies, business models, and process models in this context were discussed. It was concluded that a process model is needed for identifying and delivering business value through Information Management in DBB.

Capability 4: The capability systematically to identify and derive business value (including political, technological, social, economic and environmental value) from Information Management. Specifically, a value-driven process model is required.

8. Concluding Remarks

Over its five workshop activities, Network FOuNTAIN established six capabilities that will be important in Digital Built Britain in the coming years. These can be summarised as:

- Capability 0: Capability to gauge Information Management maturity.
- Capability 1a: Capability to establish the appropriate scope of standardisation.
- Capability 1b: Capability to design or extend existing ontologies *in general*.
- Capability 2: Capability to develop current classification systems, schema and frameworks, Uniclass 2015 *in particular*.
- Capability 3: Capability to develop Information Management software.
- Capability 4: Capability to identify and derive business value from Information Management.

Capability 0 can potentially enable and Capability 4 can potentially drive the other Capabilities. Capability 0 aligns with aspects of BS19650 (ISO 2018a,b). Capability 4 aligns with the Gemini Principles driving the creation of a National Digital Twin (CDBB 2018b). Capability 1a is the one possibly entailing some more basic research, and is positioned as a longer-term target, although it is of fundamental priority. This paper makes an important contribution to knowledge by identifying the capabilities in Information Management that will be needed by professionals as the industry in the UK and worldwide undergoes is digital transformation. The most important limitation of this work is that it is based on the views of a small (albeit influential) group of professionals and researchers.

Acknowledgements

The Network FOuNTAIN project was funded by the Centre for Digital Built Britain. The views, thoughts, and opinions expressed in the report belong solely to the authors, and not CDBB. The authors gratefully acknowledge the contributions of all workshop attendees.

References

BIM Task Group (2018). Plain Language Questions. Retrieved from https://www.thenbs.com/BIMTaskGroupLabs/questions.html on 1/5/2019.

BIM4Water (2017). The Development Procedure For Water Industry Product Data Templates. BIM4Water Standard Libraries Group. Retrieved from https://www.britishwater.co.uk/media/Download.aspx?MediaId=1717 on 1/5/2019.

Cabinet Office. (2013). The Government Soft Landings. Retrieved from https://www.cdbb.cam.ac.uk/Resources/Bimtaskgroupmaterial/GovernmentSoftLandingsSection1Introduction.pdf.

CDBB (2018a). Year One Report: Towards a digital built Britain, Retrieved from https://www.cdbb.cam.ac.uk/Resources/ResoucePublications/CDBBYearOneReport2018.pdf.

CDBB (2018b). The Gemini Principles. Retrieved from https://www.cdbb.cam.ac.uk/Resources/ResoucePublications/TheGeminiPrinciples.pdf/at_download/file.

CDE Sub Group (2018). Asset Information Management - Common Data Environment Functional Requirements. UK Government BIM Working Group, CDE Sub Group. Retrieved from https://www.cdbb.cam.ac.uk/Resources/ResoucePublications/BIMLevel2AIMCDEFunctionalRequirements20181.pdf on 1/5/2018.

CIOB (2018). BIM+: Explaining the levels of BIM. Retrieved from http://www.bimplus.co.uk/analysis/explaining-levels-bim/ on 1/5/2019.

Constructing Excellence (2006). Avanti6 February, 2015. Retrieved from http://constructingexcellence.org.uk/resources/avanti/ on 1/5/2019.

Demian, P., Yeomans, S. G., Murguia-Sanchez, D. E., West, M., Barr, S., Beach, T., ... & Home, R. (2019). Network FOuNTAIN A CDBB network: For ONTologies and information maNagement in digital built Britain. Retrieved from https://dspace.lboro.ac.uk/2134/37318 on 1/7/2019.

Demian, P., Ruikar, K., Sahu, T., & Morris, A. (2016). Three-Dimensional Information Retrieval (3DIR): Exploiting 3D Geometry and Model Topology in Information Retrieval from BIM Environments. International Journal of 3-D Information Modeling (IJ3DIM), 5(1), 67-78.

Enzer, M., Bolton, A., Boulton, C., Byles, D., Cook, A., Dobbs, L., El Hajj, P. A., et al. (2019). Roadmap for delivering the information management framework for the built environment. [Webpages]. https://doi.org/10.17863/CAM.38227

Fruchter, R., & Demian, P. (2002). CoMem: Designing an interaction experience for reuse of rich contextual knowledge from a corporate memory. AI EDAM, 16(3), 127-147.

Hackitt, J. (2018). Building a safer future: independent review of building regulations and fire safety: final report (CM9607).

ISO (2018a). ISO/DIS 19650-1.2 :2018(E): Organization of information about construction works — Information management using building information modelling — Part 1: Concepts and principles.

ISO (2018b). ISO/DIS 19650-2:2017(E): Organization of information about construction works — Information management using building information modelling — Part 2: Delivery phase of assets.

NBS (2018a). Technical Support: Classification. Retrieved from https://toolkit.thenbs.com/articles/classification#classificationtables on 1/5/2019.

NBS (2018b). What are Plain Language Questions (PLQs)? Retrieved rom https://www.thenbs.com/knowledge/what-are-plain-language-questions-plqs on 1/5/2019.

NBS (2018c). NBS BIM Toolkit. Retrieved from https://www.thenbs.com/our-tools/nbs-bim-toolkit.

NIC (2017). Data for the Public Good. A Report of the National Infrastructure Commission. Retrieved from https://www.nic.org.uk/wp-content/uploads/Data-for-the-Public-Good-NIC-Report.pdf.

Shneiderman, B. (1996). The eyes have it: A task by data type taxonomy for information visualizations. In Visual Languages, 1996. Proceedings., IEEE Symposium on (pp. 336-343). IEEE.

West, M. (2011). Developing high quality data models. Morgan Kaufmann.

West M. and Cook, A. (2018). Towards a Digital Built Britain: Introducing the Information Management Landscape. Unpublished Draft White Paper.

Exploring Deep Learning for Estimating Construction Costs during the Early Stages of Design

Xiaohua Jin[1, *], Robert Osei-Kyei[1], Varin Kant[1]
[1]Western Sydney University
[*]email: Xiaohua.Jin@westernsydney.edu.au

Abstract

Deep learning has unequivocally demonstrated far superior capabilities in solving problems than any other machine learning technique and has thus far been showcased in a wide variety of applications such as; Autonomous Cars and AlphaGo. Deep learning relies on large data sets to train models using the neural network architecture with many hidden layers. Existing studies have demonstrated deep learning as an effective alternative to standard methods of early stage cost estimation for construction building projects. These undertakings have however been limited to a small sample size of data observations and often from a singular source, which leaves an important question unanswered regarding the ability of deep learning to generalise when exposed to a large sample size. This research aims to understand how incremental increases in data size impact the performance of deep learning in estimating costs during the early stages of design. The design of this research is to collect volumes of data from project records and model these with a deep learning architecture designed from researched key literature. This research employs a quantitative approach to analysing the data. The mean square error and r-coefficient of correlation are the key markers by which the performance of the test data is to be measured against. As a model is retrained in each instance under a different set of conditions, it can be difficult to determine when a global minimum has been reached by the model and as such the best of 5 attempts will be used as the marker for analysis for each data internal. The research is at the stage of data collection and this paper reports on the literature review and research design.

Keywords: Estimating, Design, Deep Learning, Big data, Construction

1. Introduction

Technological transformative leaps eventually infiltrate and meaningfully impact most industries in the modern commercial world (Venturi, 2014). In the AEC (Architecture, Engineering and Construction) Industry, leaps in technological advancements at pivotal points in time have impacted the cumbersome ways by which projects are delivered from inception through to competition. These transformative leaps disrupt stalwart processes in the AEC Industry and historically occur at a moment of convergence when improvements in technological capabilities, barriers to utilisation and real reductions to cost occur to such an extent that the pendulum swings relatively quickly in favour of any particular technological adoption (Wynne, 2012). The next transformative leap to shape the AEC industry is pointing towards several different technological vehicles, such as; artificial intelligence (AI), the internet of things (IoT) and robotics (Kelly, 2016). The aggregation and use of data are at the heart of each of these technological vehicles in which large data sets, and machine-learned algorithms converge to drive optimal outcomes and efficiencies on order of magnitude previously unseen (Kelly, 2016). Machine learning uses algorithms that can learn from data without relying on rules-based programming. Many different forms of machine learning exist, such as multiple linear regression, decision trees and neural networks, of which many different subsets and types exist for each form (Pyle and San Jose, 2015).

Deep learning (Neural networks with deep layers) has recently separated itself from the forms of machine learning that exist today and poses as the most attractive. This is due to deep learning's ability to distinctly understand non-linear dependencies and complex relationships at a human level. The underpinning which drives the performance of these deep neural networks are large amounts of data, which can be properly trained in order to mimic the complex relationships that exist in the real world (Pyle and San Jose, 2015). Large data sets in the AEC industry exist in many forms such as drawings, schedules, quotations, applications and models and can contain many types of information such as costs, engineering details, methodologies and schedules (Martinez-Rojas *et al.*, 2015). As such there are extensively many permutations and combinations of data points that can be used for a variety of unique machine learned applications. One specific application which naturally fits well with the contextual information described above is cost estimation of building construction as there is a heavy reliance on historical data collected when formulating a predicted cost value (Skitmore and Picken, 2000; Smith *et al.*, 2016).

The research into the viability of deep neural networks when purposed for early stage cost estimation has been carried out by academic's around the world and published in journals over the years (Sontag, 1998). It is clear that the research conducted into the viability of deep learning as an alternative for cost estimation in the building construction industry has been limited to comparatively small samples of data sets. It can be inferred that due to the sensitivity of the cost data and decentralisation of data locality, researchers have been physically constrained in the volume of data available. Deep learning inherently requires large amounts of data to optimise the performance of a model, in fact incremental increases of data added to a model should improve the overall performance of the model (Foody *et al.*, 1995). The size of the data based on the parameters and network design used commonly across the research studies have not been tested under a meaningfully large data set, which would by association cover a wider spectrum of projects and permutations. A deep neural network trained under the design principles specified in the studies with large amounts of data should be able to generalise the underlying relationships to such an extent that it can outperform the adhoc abilities of an experienced estimator in order for it to deemed as a viable alternative.

Therefore, the following research questions are raised and to be answered in this study. Firstly, how does incremental increases in data size impact the performance of deep learning in estimating costs during the early stages of design? And secondly, is deep learning a viable and practical alternative to traditional methods of estimating construction costs based on the current market requirements estimators? At the time of writing this paper, the research is at the stage of data collection and this paper reports on the literature review and research design.

2. Literature Review

2.1 Stages of Design

Buildings are intrinsically a complex product to design, produce and manage given the sheer scale of the tasks being undertaken, the bespoke nature by which the design is developed and the non-linear relationships that exist between work activities. The management of cost planning activities is by extension a difficult and complex activity during the development process of a project and is critical to achieving the overarching goals of any construction project of being; on budget, on programme and adhering to quality standards (Ostrowski, 2013). Seeley described approximate estimating as "*. . . techniques which attempted to give a forecast of the probable tender figure, although the basis of the computation often left much to be desired*" (Seeley, 1972). The latter end of this definition highlights the stigma around cost estimation which has carried forward nearly 50 years later, in that the computation behind approximate estimating is said to be somewhat of a "pseudo-science" or in other words a mix between the disciples of science and art (Sundaram, 2015). There have since been various nuanced definitions and understandings on what building construction cost estimation entails by corporate bodies, researchers, authors and industry leaders.

According to the Australian Institute of Quantity Surveyors (AIQS) (2017a), a project undergoes an evolution and transformation in succinct stages from an initial brief through to tender and then construction. A cost planner is required to reassess the construction cost budget at these pivotal stages in order to ensure that the intent of the brief is being met and to identify whether the design scope is increasing beyond the view formed during the very early initial stages of the preconstruction process or whether there has been a gross miscalculation in setting the budget at the brief or outline proposal stage. The critical challenges associated with cost estimation during the early stages of pre-construction stem from a lack thereof design documentation. The minimal design at this stage of the project is by intent, as it allows various stakeholders such as architects, engineers and project managers to make dynamic decisions that are comparatively cost-effective. Whilst empowering the project team, the cost planner is inhibited in formulating a robust view of the defining project characteristics and hence an accurate assessment of cost. The cost-estimate formulated by the cost planner during these early stages of pre-construction, feeds back into the decision-making process. A vicious cycle of misinformed decision making can begin, in which an inaccurate estimate is guiding the decision making of various stakeholders. The minimal design during the early stages of pre-construction, limits the cost planner to employing only a few traditional cost estimation methods based on an underlying principle of abstracting rates to measured quantities.

2.2 Cost Estimation Techniques and Expected Accuracy

The ***superficial method*** (or otherwise known as the floor area method) is a cost estimation technique that heeds to a simplistic arithmetic model. The nuances required in the application of such a rudimentary cost estimation technique lays in the interpretation of the variables, "Area" and "Rate". Gross Floor Area (GFA) has inadvertently provided the building construction industry with a consistent framework by which to benchmark project costs. Common alternate frameworks include Gross Building Area (GBA), Net Lettable Area (NLA) and Gross Lettable Area (GLA). On the other hand, the "Rate" variable is increasingly open to the cost planner's judgement in estimating a unit rate which reflects the actual cost. As a starting point, a cost planner traditionally filters and isolates historical projects based on a set of similar characteristics such as size, sector, building envelope, storeys, location and height, forming a basis for a \$/m2 rate applicable for the given project to be estimated. At this stage, a cost-planner will have to draw upon a wide variety of internal and external sources as well as individual experiences in order to form a view on the adjustments required to the unit rate in order to reflect changes in factors such as project location, economic conditions, inflation, project design and risk (Smith *et al.*, 2016). The simplicity built-in to the technique gives the cost planner a high degree of flexibility and discretion which can leave room for individual bias, errors in judgement and cognitive dissonance, which edges the superficial method towards the non-scientific realm.

The ***functional area method*** has its foundations built-up on the principles of the superficial method but deviates by clustering spatial areas based on its functional use and applying specific $/m2 rates to each of the compartmentalised areas. The numerical variable represents any number of functional areas such as; residential, commercial, basement and lobby spaces. The clustering of areas by functional use, gear the cost planner to apply realistic $/m2 rates which can reflect the design intent of the project veraciously unlike the superficial method, which essentially is assessing a project as a single monolithic item. Whilst the functional area method is more accurate at estimating costs comparatively to the superficial method during the early stages of pre-construction, its challenges lay in the lack thereof a framework which is consistent, valid, reliable and reproduceable. The superficial method has an area framework which is singularly based and allows for easy translations between a wide variety of projects unlike the functional area method that is multiplicity based and can be difficult to translate between different spatial intents of projects. The effective utilisation of this technique requires a consistent framework by which projects are measured and rated (Smith *et al.*, 2016).

The margin of error demonstrated and expected in the AEC industry between estimated costs against the actual costs of a construction building project gives credence to the pass/fail nature of when an estimate is within an acceptable tolerance and when it is not. The performance of deep learning for early stage cost estimation against markers expected by most professionals gives an insight into the real-life use case for such a method. Cheung *et al.* (2008) examined the attitudes of clients and estimators towards estimating errors by way of a questionnaire survey in Hong Kong. In reviewing the acceptable errors held by clients for different sectors and market conditions, it is evident that based on any given set of conditions the acceptable error percentage could range from as low as 7.06% for overestimates in a good market for industrial projects to as high as 23.84% for overestimates in a bad market for school projects. In averaging the acceptable percentage tolerance across all the different permutations and combinations of conditions, clients averaged an acceptable tolerance error of 13.74% whilst estimators an error of 13.55%. These averages suggest that on average an error of 14% is viewed as perceptually, the acceptable tolerance between estimated and actual costs. It is important to acknowledge that this bias is not a reflection on actual discrepancies but rather on perception which may or may not be influenced by quantitative facts.

2.3 Deep Learning for Cost Estimation

Deep learning exists as a class of machine learning algorithms that exhibit features which include a cascading of multiple layers of nonlinear processing units for feature extraction and transformation, learning environments to be within supervised or unsupervised manners and the ability to abstract from levels within a hierarchy of concepts (Deng and Dong, 2014). At this time, the most popularised and documented form of deep learning to exist is in the form of deep neural networks, which in itself is an artificial neural network (ANN) but distinguished due to the number of hidden layers in the network, thus giving the artificial neural network, the distinction of being a deep neural network (Bengio, 2009). An artificial neural network is a machine learned system in which data dictates the framework of any given application instead of explicit logics scripted. The conceptual architecture of an ANN encapsulates a framework in which a number of inputs are feed forward into a neuron which maintains an activation function. Each neuron activates in the presence of certain observations and can generalise theoretically the class of inputs which form the path to a highly accurate prediction. An activation map is trained at each neuron as it is re-modelled, and a fully connected network exists between the inputs and neurons, through to the corresponding output. Activation functions which can be used at each of the neurons varies between Sigmoid, RELU, tanh and many other variants. A deep neural network layers neuron in hidden layers between the inputs and outputs and this is the distinction that gives a neural network its deepness (Olafenwa, 2018).

Kim and An (2004) compared a number of non-traditional cost estimation models for construction projects namely, case-based reasoning, neural networks and multiple regression analysis. A sample of 530 projects are used in this study with 40 projects out of the 530 used to test the performance of each of the non-traditional methods. Neural networks outperformed case-based reasoning which outperformed multiple linear regression, however the time to reach global minima posed as an issue as the varied results could not be extrapolated in definition. The input variables used for this study include, year of construction, gross floor area, storeys, total units, duration of construction, roof type, foundation type, usage of basement and finishing grades. On average 90% of the test values fell within 10% of the actual cost when modelled as a neural network that is optimised. The paper did not publish, disclose or further explain the rationale behind the number of trials required to achieve global minima in the neural network and hence an optimised result. A sample of 10% (or 40 projects) is on the lighter end but given the constraints of data it is within reason why more projects are used to train the model instead of testing its performance to further validate the model's framework. The variables used in this model are far reaching in terms of information that may be available to be considered during the early stages of design. There is question mark regarding the inputs concerning the construction duration, roof type, foundation type and finishing grades for which exact information is quite limited, as in some cases design is required to be further developed in order to flush out the exact details of each input (Smith *et al.*, 2016).

Chandanshive and Kambekar (2014) developed a neural network model based on MATLAB's neural net fitting tool, using the Levenberg-Marquadt algorithm. 58 projects are used in the modelling of construction costs based on 9 parameters, which include; site area, ground floor area, typical floor area, height of a building, quantity of shear wall, quantity of exterior wall, number of columns, foundation type, number of householders and total structural skeleton cost. The artificial neural network used for training, validation and training phase 70%, 15% and 15% respectively. The model is trained for between 1 and 10 hidden layers, demonstrating progressively higher overall regression's as the number of hidden layers is increased up to 10. The study did not address the accuracy of the model in terms of the practical implications in the industry and only viewed the results from the lens of statistical analyses such as mean square error and regression values. The research paper did not delve into the performance of the model from a standpoint that is digestible for analysis that could draw back to real life implications or comparatives. Using 58 projects for a study of this nature, is extremely small as well, the sample size does not dictate the use of artificial neural networks, especially with 10 hidden layers, as the framework is exposed to being over-fitted due to the small number of observations.

Arafa and Alqedra (2011) conducted a study into the use of artificial neural networks for early stage cost estimation of build projects in Gaza, Palestine. This study followed a very similar approach to that of which has been described in the two studies above except that 71 projects are along with a different set of parameters. These 7 variables include; ground floor area, typical floor area, number of storeys, number of columns, type of footing, number of elevators and number of rooms. The model had one hidden layer and tested 12 projects against its trained model. The correlation of coefficient is 0.97 demonstrating a positive correlation between actual and predicted values, however this did not address the performance of the model from a standpoint that is digestible for analysis that could draw back to real life implications or comparatives. In a sensitivity measure conducted, they found that no. of stories, ground floor and no, of elevators are the most influential in dictating the output of the mode. Using 71 projects for a study of this nature, is extremely small as well, the sample size does not dictate the use of artificial neural networks, especially with 10 hidden layers, as the framework is exposed to being over-fitted due to the small number of observations.

3. Research Methodology

The methodology employed in this study is tailored to meet its design requirements, which mainly requires the size of the data to be abnormally large in comparison to studies carried out of a similar nature. This abnormality requires a unique approach in that the data are collected from a secondary source, from which many options are examined. As a result, a large portion of the findings and analysis are limited by the scope of the data collected and not necessarily by the intent, as would be suffice when primary sources for data are utilised for collection(Oluwatosin Ajayi, 2017). The study employs a quantitative approach to discerning results and analyses for discussion(Creswell, 2013).

3.1 Design Requirements

The design requirements of the data that need to be collected for this study can be divided into two parts. The first part is concerned with the number of data observations that needed to be collected. As the basis of this study is concerned with the performance of deep learning for cost estimation at scale, it is critical that the choice of sourcing is able to account for the large number of data observations required. The second part is concerned with the variables that are to be available for choice when modelling the neural network. As mentioned in the literature review, there are many inputs which need to be considered from previously published research papers. As studies previously carried out of a similar nature had demonstrated, it is critical that inputs that are at the project level are available to be modelled. The number of data observations used in previous studies ranged from 34-530 and as such it is determined that at least double the amount of data observations are required in order for this study to meaningfully research the impact of a larger data set when used for this application. The variables (or inputs) required for the design would ideally have been as many as possible, given the structure of a neural network is to disseminate the complex correlations that may or may not exist between variables and to essentially remove the human dissemination of ideologue and thus allowing the model to make its own determine on these relationships (Aamodt and Plaza, 1994). As such, there exist a mutual number of inputs that would be required for this study. These variables include floor area, storeys and functional use for the inputs and the value of the project as the output. Any additional inputs are to be treated as secondary but still important to achieving the level of accuracy required. A dataset of a size greater than 1000 observations and that contains data about floor area, storeys and functional use of projects at a minimum form the minimum design requirement needed to be achieved for this study. If several different sources and collection methods meet this criterion, the selection criteria will then be based on a combination of factors including number of data observations, data quality, reliability and number of secondary variables.

3.2 Data Collection

The design requirements of the data to be collected immediately nullify the option to source data from primary sources. Primary sources would include methods such as interviews, questionaries or direct data from the source such as a government entity voluntarily disclosing the financials of a project they had undertaken (Oluwatosin Ajayi, 2017). As the fundamental requirements of the study require a significant amount of data observations, primary sources which would pose a challenge from a practical standpoint as that the collection of mass amounts of data would require the collaboration of many participants. The decentralised market forces that exist in the AEC industry means that many companies only hold a small portion of information of the total construction market and thus gathering at least 1000 data observations would require the participation of too many organisations (Flanagan *et al.*, 2007). Additionally, the type of data requested, in this case the costings of a project is a very sensitive form of data and from a confidentiality point of view, it would pose as an additional challenge if such information is to be sourced directly from stakeholders (Smith *et al.*, 2016). The same principles described can be viewed from the lens of other stakeholders such as clients or quantity surveyors, in both these cases there exist varying levels of decentralisation and sensitivities that would generally be too profound to be selected as a source for data collection.

It is due to the constraints described above, that it is determined a secondary source is needed which can not only meet the design objectives but reasonably be objectified as being reliable, valid and accurate (Oluwatosin Ajayi, 2017). Two types of secondary sources are considered for this study, the first being that which exists in public records and the second being that which is published by the private sector. Public records seemed to be the logical path for this study as the records can reasonably be determined as being reliable, valid and accurate due to the regulatory and legislative nature of the records. The secondary sources of public records considered are that which are published by the Australian Bureau of Statistics (ABS), Data61 and Local Government Councils. The ABS publish a wide range of quantitative figures related to the building industry covering a spectrum of categories and formats which determine key economic indicators. At the project level however, the ABS due to its sensitiveness does not disclose project details and thus could not be used for this study (2017b). Data61 is a data initiative by the government which encourages the use of government data by opening up records held by the government for the wide benefit of the community. However, Data61 does not have the required data published and needs a request to be lodged in order to be disclosed. As there is no guarantee on if this information would be disclosed, again due to the issue of sensitivity and as well the amount of time needed to process a request, this option is also rendered null. The last option looked at using process automation to extract information from development applications lodged with councils. Each local council generally has a development application portal available for the public to access as public development notifications. Although the information varies from council to council in the way that it is presented and what is available to view, generally one could access some project details such as project location and cost, but any further information would require manual data entry from associated documents and drawings. This option is feasible if there is enough manpower or automation to classify the required information from council websites and index data accordingly.

Secondary sources from private entities seem to be the next logical source for secondary data that fit the design requirements of this study. In exploring sources from the private sector, it is determined that the viable options include CoreLogic's Cordell Connect and Macromonitor’s Key Project List. Although being project specific in terms of identifying the project, its cost and when it would be constructed, Macromonitor’s Key Project List does not provide any further details that are required as per the design criteria. On the other hand, Core Logic’s Cordell Connect is an online platform that published projects in Australia with a lot of information. This information includes many project specific details along with ancillary information such as consultants and contact numbers. Cordell Connect has a large database of projects that are researched and indexed by a team of 60 in Australia. These projects have their information verified by council minutes taken at meetings and by industry personnel. This poses as the most suitable option for this study as it can be reasonably extrapolated that the data is reliable, valid and accurate based on the through research and processes being executed at Core Logic. As the data exist online in a platform it is critical that the data stored within each of the projects record can be extracted in a manner that is usable for MATLAB to model. In this case the data is required to be extracted into a .csv file that follows the required standard principles of data design in which each row is a data observation (a single project) and each of the rows represents an input (or variable) (Wickham and Grolemund, 2017). Core Logic has data exported in a certain way to a .csv file with a maximum capacity of 500 projects to be exported at a time. As such a R-Script is compiled which can transform and merge the data from these raw files into a single .csv file, ready to be modelled.

3.3 Modelling and Analysis

The neural network modelling of data will be carried out in MATLAB, a popular programming language used for a variety of purposes particularly for science and engineering. Its use for deep learning is particularly popular and powerful due to the development of proprietary tool boxes which minimise the technical programming skills required to model data for deep learning. The tool box used for this study is the neural net fitting app, which is designed to map a data set of numeric inputs against a set of numeric targets. In this case the variables are required to be numeric and the data which exist as factors (i.e. categories) are converted to individual variables with 0 representing no and 1 represent yes. The study uses the very fundamental selection of parameters that can be amended for such a use case. In this case the Levenberg-Marquardt backpropagation algorithm is used along with a threshold of 70% of data to be used to train the model and 15% to validate the model to prevent the model from over fitting. The remaining 15% of the data is used to test the trained model. The splits can be amended and adjusted as required but the split used for this study is to be kept as a constant variable using the default values in MATLAB’s tool box. The number of layers used for this model is 10 with sigmoid hidden neurons. The variable which is being assessed for this study is the number of data observations to be used for the training of the neural network model. For the purposes of this study the number of data observations will begin by training a model at 100 observations and double each time over as a new interval is introduced. This means that the next set of data observations to be assessed is 200 and then 400 and so on. The data observations which will be used to train the model and then be tested are randomly assigned and kept consistent over 5 different trials with the best trial used as the basis for assessment. The reason the best trial is used as neural networks aim to achieve a global minima and it is very common for training of a data set to begin down a particular path and achieve only local minima(Birui, 1989).

The neural net fitting tool outputs the results as a regression plot between the targeted values and the values outputted by the trained model. The strength of the correlation is then assessed by the coefficient of correlation of the line of regression. This value is between -1 and 1 with a value of -1 meaning that the two values pitted on the x and y axis are moving perfectly not in unison whilst a value of 1 means that the two values pitted on the x and y axis are moving perfectly in unison. A value of 1 in this study would indicate that the model has perfectly generalised and modelled the complex relationships that exist between the inputs of the deep neural network and is able to predict exactly the value of a construction project based on the inputs used to train the model. The coefficient of correlation is one of the key markers used in this study to compare the performance of the deep neural network at several different data set size intervals. The second marker used to assess the performance of the model is the RMSE, which is the absolute value of the mean difference between the targets and outputs. This is a holistic number that is comparable to the values of the projects used to train the model and given an insight into the average bias between targets and outputs. The third marker used to assess the performance of the model is the “E-Value”, which is a value to give insight into the practicality of the model in the real world by assessing its performance against the expected performance of an estimator by industry standards. The bias expected to be achieved by estimators is between 10% and 14%, when considering actual and perceptual thresholds of acceptability. As a result, the E-Value is to be analysed against projects which predict values within 10% of the actual value and is to be referred to as E-10 for this study, whilst projects which predict values within 20% of the actual value known as E-20. The results of each of these markers give insight to a unique set of analyses.

4. Summary

This study aims to extend upon previous research focusing on the utilisation of deep learning as a non-traditional method in estimating the construction costs for construction projects during the early stages of design when project information is limited. The research methodology used for this study was formed around two central design requirements of the data set, the first being the need for the number of data observations to be at least doubled the number of projects than previous similar studies. As such an arbitrary number of 1000 of projects was deemed as the minimum threshold of projects required to be modelled for this study, which focused on the scalability of deep learning for estimating costs during the early stages of design. The second design requirement of the data was concerned with the variables that would be available to be modelled in the neural network. In assessing similar studies, a mutual pool of project characteristics is evident as the most sensitive to cost. These parameters included floor area, number of stories and functional use. Secondary inputs or variables would be critical in disseminating and modelling the complex interplay between each of these variables but could be given some latitude in terms of the make-up of each of these parameters. Floor area, storeys and functional use were essential details of a project required to be modelled for the purposes of this study.

The data source selected which could meet the design objectives best were from CoreLogic’s Cordell Connect, a secondary private source that could reasonably be considered to be accurate, reliable and valid. The variables of the model including the algorithm used, randomised data sample and validation/testing threshold are kept constant in order to test the variable of data size on the performance of the neural network. Data intervals of 100, 200, 400, 800 and 1600 are the intervals measured, from a best of 5 trials. From a practicality point of view, the model’s performance is pegged against a percentage of projects which are able to meet the industry thresholds of 10% and 20%.

This paper has demonstrated the challenges that are present in utilising deep learning for estimating construction costs at scale and has presented the gaps that exist in current research as it relates to the application of this method from a practicality point of view in that the lack of project information makes it difficult for deep learning to generalise and model the complex behaviour of a wide spectrum of projects. Innovative approaches which aim to tackle this problem with an added caveat or a different approach may hold the key to successfully deploying deep learning for estimation of construction costs during the early stages of design at scale.

References

Aamodt, A. & Plaza, E., 1994. Case-Based Reasoning: Foundational Issues, Methodogical Variations, and System Approaches. AI Communications, 7(1), pp. 39-59.

Aibinu Ayodeji, A. & Pasco, T., 2008. The accuracy of pre-tender building cost estimates. Construction Management and Economics, 26(12), pp. 1257-1269.

AIQS, 2017. 2016-2017 Annual Report, Sydney: s.n.

Arafa, M. & Alqedra, M. A., 2011. Early Stage Cost Estimation of Buildings Construction Projects using Artifical Neural Networks. Journal of Artifical Intelligence, 4(1), pp. 63-75.

Australian Bureau of Statistics, 2017. Privacy, Confidentiality and Security. [Online] Available at: http://www.abs.gov.au/websitedbs/censushome.nsf/home/privacy [Accessed 12 June 2018].

Bell, E. & Bryman, A., 2015. Business Research Methods. 4th ed. Oxford: Oxford University Press.

Bengio, Y., 2009. Foundations and Trends in Machine Learning. 1st ed. Ishington: s.n.

Birui, B., 1989. A new approach for finding the global minimum of error function of neural networks. Neural Networks, 2(5), pp. 367-373.

Chandanshive, V. B. & Kambekar, A. R., 2014. Prediction of Early Stage Construction Cost of Building Projects Using Artifical Neural Netork. International Journal of Scientific & Engineering Research, 5(7), pp. 453-463.

Cheng, Y.-M., 2014. An Exploration into Cost-Influencing Factors on Construction Projects. International Journal of Project Management, 32(1), pp. 850-860.

Creswell, J. W., 2013. Research Design: Qualitative, Quantaitative, and Mixed Method Approaches. 4th ed. s.l.:SAGE Publications Inc.

Deng, L. & Dong, Y., 2014. Deep Learning: Methods and Applications. 1st ed. Ishington: s.n.

Flanagan, R., Lu, W., Shen, L. & Jewell, C., 2007. Competitiveness in construction: a critical review of research. Construction Management and Economics, 25(9), pp. 989-1000.

Foody, G., Mcculloch, M. & Yates, W., 1995. The effect of training set size and composition on artificial neural network classification. International Journal of Remote Sensing, 16(9), pp. 1707-1723.

Franco K. T. Cheung, Margie W. L. Wong & Martin Skitmore (2008) A study of clients' and estimators' tolerance towards estimating errors, Construction Management and Economics, 26:4, 349-362

Genpact Research Institute, 2014. The Impact of Technology on Business Process Operations. s.l., Genpact.

Gunner, J. & Skitmore, M., 1999. Comparative Analysis of Pre-bid Forecasting of Building Prices based on Singapore Data. Construction Management and Economics, 17(5), pp. 635-646.

Jin, R., Han, S., Hyun, C. & Kim, J., 2014. Improving Accuracy of Early Stage Cost Estimation by Revising Categoical Variable in a Case-Based Reasoning Model. Journal of Construction Engineering and Management, 140(7).

K. Y. Cheung, F., W. L. Wong, M. & Skitmore, M., 2010. A study of clients' and estimators' tolerance. Construction Management and Economics, 26(4), pp. 349-362.

Kelly, K., 2016. The Inevitable : Understanding the 12 Technological Forces That Will Shape Our Future. 1st ed. New York: Random House USA.

Kim, G.-H. & An, S.-H. K. K.-I., 2004. Comparison of construction cost estimating models based on regression analysis, neural networks, and case-based reasoning. Building and Environment, 39(10), pp. 1235-1242.

Kunce, J. & Chatterjee, S., 2017. A Machine-Learning Approach to Parameter Estimation, Virgina: CAS .

Martinez-Rojas, M., Marin, N. & Vila, A., 2015. The Role of Information Technologies to Address Data Handling in Construction Project Management. Journal of Computing in Civil Engineering 3, 30(4).

MATLAB, n.d. Fit Data with a Shallow Neural Network. [Online] Available at: https://au.mathworks.com/help/deeplearning/gs/fit-data-with-a-neural-network.html

Newman, I. & Benz, C. R., 1998. Qualitative-Quantitative Research Methodology. 1st ed. s.l.:SIU Press.

Olafenwa, J., 2018. Introduction to Neural Networks, s.l.: Medium.

Oluwatosin Ajayi, V., 2017. Primary Sources of Data and Secondary Sources of Data, Makurdi: s.n.

Ostrowski, S. D., 2013. Estimating and Cost Planning Using the New Rules of Measurement. 1st ed. Somerset: Wiley.

Pacey, A., 2007. Medieval Architectural Drawing. s.l.:Tempus Publishing.

Pasco, T. & Aibinu, A. A., 2008. The Accuracy of Pre-Tender Building Cost Estimates in Australia. Construction Management and Economics, 26(12), pp. 1257-1269.

Pyle, D. & San Jose, C., 2015. An executive's guide to machine learning. McKinsey Quartely, September.

Seeley, I., 1972. Building Economics: Appraisal and Control of Building Design Cost and Efficiency. 1st ed. London: Macmillan Educaktion.

Skitmore, M. & Picken, D. H., 2000. The Accuracy of Pre-tender Building Price Forecasts: An Analysis of USA Data. Australian Institute of Quantity Surveyors Referred Journal , 4(1), pp. 33-39.

Smith, J. et al., 2016. Building Cost Planning for Design Team. 3rd ed. London: Taylor and Francis Group.

Sontag, E. D., 1998. VC Dimension of Neural Networks. Neural Networks and Machine Learning, pp. 69-95.

Sundaram, R., 2015. Cost Estimating: Art, Science or Both?. 20 08.

Venturi, A., 2014. Impact of Technology on Mangement and Organisations. 08 12.

Wickham, H. & Grolemund, G., 2017. R for Data Scuebce. 1st ed. s.l.:O'Reily.

Wynne, A., 2012. CAD : The Greatest Advance in Construction History. 05 09.

Collaboration support for 3D and 4D models: A pedagogical experiment applied to wooden construction

Veronika Bolshakova[1,2]*, Gilles Halin[1,3], Annie Guerriero[4], Franck Besançon[1,5]

[1]UMR n°3495 Modèles et simulations pour l'Architecture et le Patrimoine Centre de Recherche en Architecture et Ingénierie – MAP-CRAI, ENSAN, Nancy, France ;
[2]Centre National de la Recherche scientifique – CNRS, France
[3]Université de Lorraine, Nancy, France
[4]Luxembourg Institute of Science and Technology – LIST, Esch-sur-Alzette, Luxembourg
[5]École Nationale Supérieure d'Architecture de Nancy – ENSAN
[*]e-mail : bolshakova@crai.archi.fr

Abstract

Through this research, we review a two-year pedagogical experiment to highlight the necessary specifications and to continue to progress towards a proposition of a new collaboration and decision-making support, well adapted to the needs of Architecture Engineering Construction. This paper presents observations from a pedagogical experiment on synchronous collective decision-making by users via digital project documents on a touch table. The experiment offers a unique context for our research on multidisciplinary collaboration observations and for 3D or 4D model use studies. Our experiment aims, first, to survey the user-perceived utility of such digital support with natural user interactions and collate suggestions for improvements to the support. For the research, both individual and group perceptions are important. Second, we describe a decision-making session actors' activity and interactions. The results will contribute to the design a collaborative decision-making support.

Keywords: Synchronous collaboration, Pedagogical experiment, 3D models, 4D models, NUI

1. Digital collaboration

Team meetings and collective decision-making (DM) have always been a part of construction project development, where multidisciplinary cooperation requires a significant effort from project stakeholders (Staub-French & Khanzode, 2007). For more than a decade, project development has used digital tools and Building Information Modeling (BIM) as common instruments (Kensek, 2014). Project teams use BIM as an information source for DM, thus they need an efficient digital collaboration environment (Achten, 2002), with quality interactions (Tory, Staub-French, Po, & Wu, 2008).

Professionals and academia continue their research for better ways to collaborate and to manage projects more efficiently (Oxman, 2008). Following this global dynamic, pedagogical experimentation needs to progress in step with the industry (Pikas, Sacks, & Hazzan, 2013). Academia is well positioned to develop new methods of innovation, knowledge growth and transmission of practices, in addition, academic framework provides a good context for experiments.

This paper summarizes a pedagogical experiment on synchronous collective decision-making with a digital support for project documents visualization and interactions: a multi-touch table with the synchronous co-located collaboration software "Shariiing"1 by "Immersion"2. The Section 2 of the paper overviews the pedagogical context of experiment, provides specifications for the Digital

1 https://www.shariiing.com/
2 https://www.immersion.fr/

Collaboration Table and describes Collaboration Sessions. It concludes with a description of the experiment feedback collection methods. Next, the Section 3 presents main findings on DCT usability scores by different user categories, and their suggestions for the collaboration support improvements. Finally, the feedback results are emphasized in discussion section, and followed by experiment conclusion and future perspectives.

Also, this study is a part of an international research project 4D Collab3, which aims to the design a new collaborative 4D-based (3D+time) decision-making support. The project team is composed of research and industry partners (including "Immersion"). The pedagogical experiment results will contribute, together with professionals' collaboration experiments (not covered by this paper), to design with 4D Collab the new collaboration tool.

2. Overview of the experiment context and methods

2.1 Main experiment steps

The *digital collaboration pedagogical experiment* (the experiment) introduced a digital support for weekly meetings on project progress. Such support has to offer a homogenous interface for all project documents to avoid software switching. Also, it must offer democratic interactions, such as used in natural user interfaces (Steinberg, 2012), along with ease of learning for participants as well.

The experiment had two Phases, the Phase 1 in 2018 and the Phase 2 in 2019 (Fig.1). The Phase 1 was conducted for the Wood Challenge[4] (Section 2.2) exercise in 2018, the Step 1: Wood Challenge, design and construction project phases; Step 2: collection of the users feedback and the adjustments to the collaboration sessions (Section 2.3). The feedback showed the utility of digital collaboration technology and suggested ways for next year improvements. In Phase 2, as Step 0, with the aim of training all the students to be efficient with a digital collaboration table during the upcoming Wood Challenge 2019, the table was introduced to them in the 1st semester for a Design Project. Steps 1, 2 have followed to conclude the 2nd phase of the experiment.

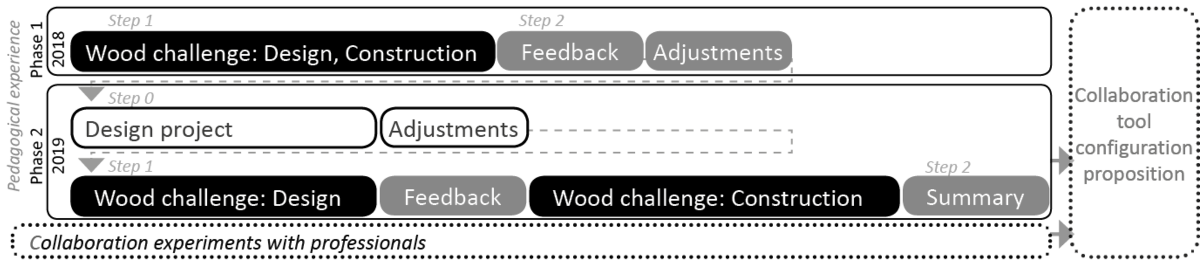


Figure 1: Schema of the digital collaboration experiment steps

2.2 Pedagogical exercise: 'Wood Challenge'

Every year, at ENSTIB 5 Engineering School of Wood Technologies and Industry, the "Architecture, Wood, Construction" 6 postgraduate program launches a pedagogical design and construction exercise called "Wood Challenge"7. The challenge's main tasks are to design and then build, in teams, a small project with a wooden structure (Fig. 2). Hence, it encourages students to foresee possible problems with their design choices, and to anticipate the answers to construction problems.

The students work in multidisciplinary teams, comprising of an architect, a wood structural engineer and a civil engineer. Also, every team has two additional members: a wood construction professional and an exchange student in architecture or engineering. The diversity of the team

3 https://www.4dcollab-project.eu/
4 Original French Défis du Bois (http://www.defisbois.fr/)
5 École Nationale Supérieure des Technologies et Industries du Bois (http://www.enstib.univ-lorraine.fr/fr/)
6 Original French «Architecture Bois Construction"(http://www.nancy.archi.fr/fr/master-genie-civil-1.html)
7 Original French « Défis du Bois » (http://www.defisbois.fr/)

emphasizes the importance of efficient communication and collaboration to the students. All teams work on a defined project type, which varies every year with the same deadline and technical requirements (quantity of materials, structural elements, tools, etc.). Once the design and pre-construction preparations have been completed (6-7 weeks in the beginning of the winter semester), the teams then proceed to construction (1 week in May). The projects are fabricated and assembled on campus. They must not exceed a surface of 15m2 and a height of 3.8m, and have no more than 10 disassembled modules or elements in order to fit into a truck for transportation to the project installation site. The restricted construction time and added competition element fosters students' abilities to foresee many construction organizational aspects and see optimization for the project design and construction.

Figure 2: Examples of Wood Challenge projects

2.3 Description of the Digital Collaboration Table

Teachers and students weekly gathered around a digital collaboration table (DCT) for project review meetings. The DCT's main element is a multi-touch screen (46" HD, infra-red touch recognition frame), which is embedded in a wooden table frame (Fig. 3). The screen is connected to a PC running "Shariiing" software, a multiuser collaboration environment by "Immersion". The software versions: "Shariiing Research" in 2018 (Fig. 3), "Shariiing Advanced" 8 in 2019 (Fig. 4).

Users interacted with the table with touch gestures (fingers), simple touch-pen, some used a wireless mouse to manipulate distant laptop. The use of Shariiing allows: 1. to visualize construction project documents (plans, sections, 3D models, schedules, etc.), 2. to share the same view even being on different sides of the table 3. to manipulate the documents with touch gestures ("move", "pinch", "zoom", "drag", "click"), 4. to annotate temporarily, permanently (Fig. 3), 5. to sketch.

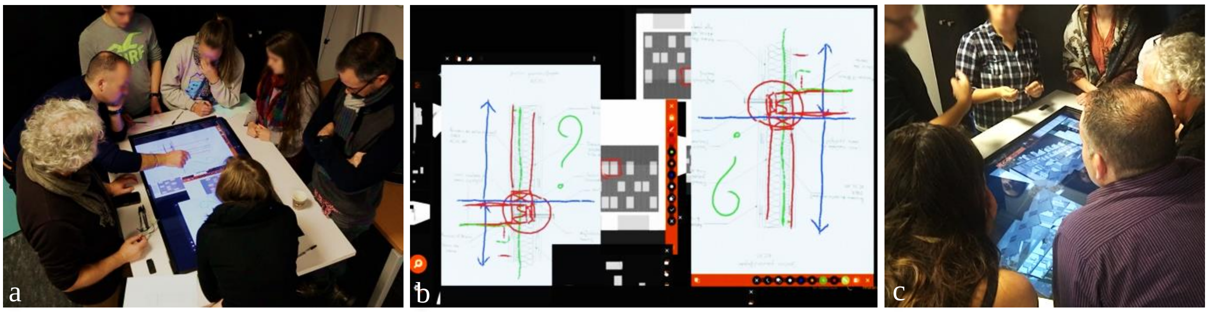


Figure 3: DCS with Shariiing Research: a,b façade detail annotation, c. 3D visualization and discussion

8 Shariiing specifications and functionalities (https://www.shariiing.com/data/documentation/Shariiing%20specifications.pdf)

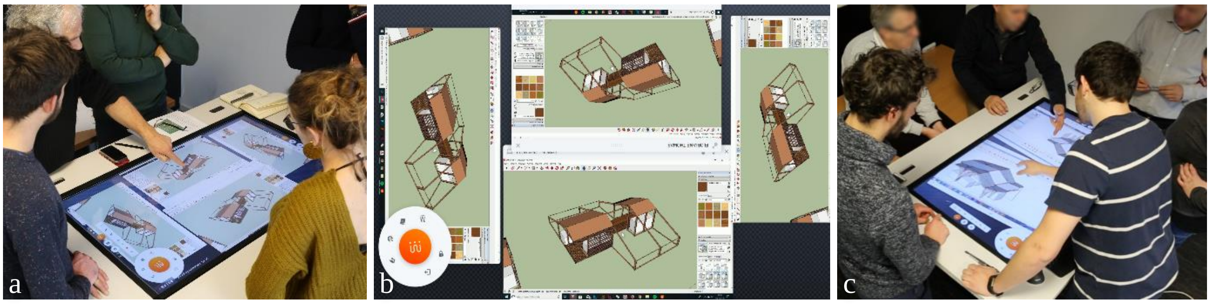


Figure 4: Digital Collaboration Session with Shariiing Advanced, interactions with 3D models

The main principle of the software use is the same for these versions, the Advanced version's interface is more minimalist and offers more fluid interactions, also 3D models visualization is offered with the screen sharing. For now users may only save an annotation on a project document as a new 2D image (screenshot). With Shariiing Research, the 3D model (.ifc, .obj) visualization and fluid interactions are possible, but it does not allow access to the model hierarchy. However, DCT offers visualization and touch interactions with a distant user. Thus, when using Shariiing Advanced, it is possible to share a view from users' laptop with a BIM viewer or design software (e.g. Cadwork (Fig.6a), Navisworks (Fig.6d), SketchUp (Fig.4a,b), etc.) directly to the collaboration environment, and to keep natural interactions and simple annotations (Fig.4a,b).

Further research aims to better adapt mentioned functionalities to AEC needs. In addition, we must acknowledge the equipment limitations, such as the screen size and resolution, or team's collaboration methodology.

2.4 Digital Collaboration Sessions (DCS) description

The session's main purpose was project review, starting with a brief presentation by the students of their progress to the professors. An architect, a structure engineer and a construction specialist were representing the pedagogical participants of DCS. The choice of the present professionals depended on the session purpose and on the project progress stage. They provided professional expertise and also represented a project client. For the Wood Challenge 2019, the mean session durations were augmenting with the project progress: 19 minutes in the beginning, 28 minutes in the end. In general, minimum session duration was 13 minutes through all project progress, and maximum session time was also augmenting from 29 minutes for the first session to 53 min to the last one. For Wood Challenge 2018, mean DCS duration was 23 minutes with a maximum of 37 minutes and a minimum of 18 min.

For Wood Challenge 2018 the design and construction subject were a pavilion9 for a botanical garden in Nancy, France. From the 10 student teams, only 2 interested in technology teams, as a part of experiment, were using the DCT for their weekly meetings (Digital Collaboration Sessions) with the pedagogical team members during the Design phase. Both teams were using plans, sections, rendered images, quantifications and 3D models for design development and value engineering at the meetings (Fig. 5a). Only one team managed to prepare a 4D model (Navisworks screenshot Fig. 5c, build structure Fig.2a). Yet, during the construction, the students preferred to rely mostly on printed project documentation, thus the 4D model was consulted only once a day by one member of the team (construction management role) for a better understanding of the assembled details and for monitoring.

9 Pavilions "Lignea camera"http://www.defisbois.fr/editions/edition-2018-lignea-camera/

Figure 5. a. Collective decision-making at Design phase in 2018 b.3D model review at Construction phase
c.4D simulation for one module assembling length estimation and progress monitoring

Together with the feedback (Sections 3.1, 3.2) on DCT improvements for AEC needs, students and professors suggested for the next year to introduce the DCT before the challenge. Thus, the table was used during autumn semester to work on a design project (reconstruction of an industrial site for student housing, residential buildings and a kindergarten) (Fig. 3). The teams had time to get experience with digital support for their weekly meetings, and to become independent users for their Wood Challenge. However, not all of the sessions' participants had an equal amount of time to interact with the DCT due to a larger number of participants. Also, 4D simulations were introduced to the students, and some of them decided to integrate them into the final project folder (digital) along with the project plans, sections, 3D model, calculations and quantifications. Table 1 synopsizes elements of DCS organization.

Finally, after training with the Design project, all the teams of Wood Challenge 2019 were using DCT for their weekly meetings with the pedagogical team during the Design phase of the challenge project (Fig.6). A new version of collaboration software (Shariiing Advanced) was installed on the DCT, to answer students requests for more familiar to them 3D models view (from their personal 3D modeling software interfaces) (Fig. 6a, 6b), and requests for more fluid interactions. All the teams were using a 3D model as a main discussion support. During the 2 final sessions, 5 student teams used 4D simulations (Fig.6d) to illustrate a construction sequence and logics for the elements of the project.

Table 1: Digital Collaboration summary for Wood Challenge 2108 and 2109, for Design Project

	Wood Challenge 2018	Design Project	Wood Challenge 2019
Project design weeks / construction weeks	6/1	12/-	6/1
Digital collaboration sessions (DCS) number	3	4	4
All Student teams / Teams participating in DCS	10/2	5/5	10/10
Number of Teams using 3D / 4D (at DCS)	2/-	5/2	10/5
Participants per one DCS Students + Professors	3 + 2 or 3	5 + 2 or 3	3 + 2 or 3

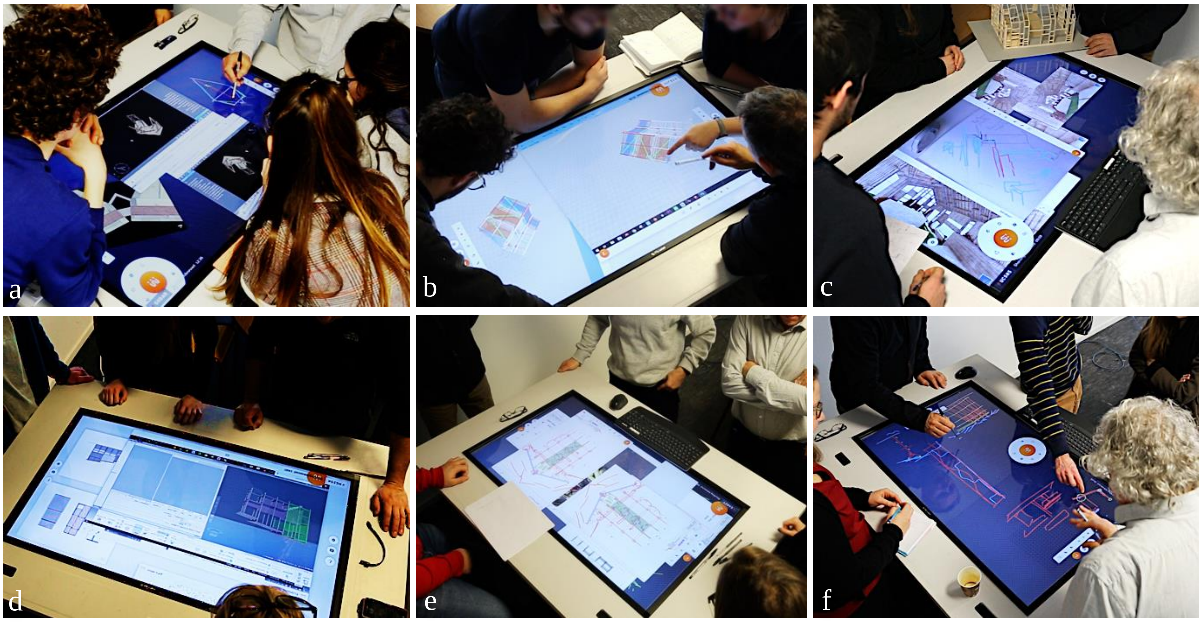


Figure 6: 2019, Examples of interactions: (a) 3D visualization and sketching on background, (b) 3D model manipulation and pointing, (c) rendered images review and sketching, (d) plans, sections, 4D simulation visualization, (e) section permanent annotations, (f) background sketching.

2.5 Research questions and Feedback collection tools

Naturally, every construction project is unique. A stakeholders team collaboration strongly depends on a project type. Their synchronous collaboration and decision-making depend on meeting types, which require specific meeting objective documents and access to group interactions. In order to design a collaboration support tool with a well-adapted to AEC users interface and collaboration method we study the use of DCT by Wood Challenge participants. With this study, we aimed to evaluate:

- Utility and usability of the digital collaboration support (i.e. interactive table & Shariiing) and to emphasize advantages and current limits of such tool through the users feedback.
- Perceived role of 3D and 4D models at discussions on the pre-construction phase

Also, for this study, with DCS observations, we aimed to better portray decision-making dynamics and main aspects, such as: time of the session, documents used for discussion, interaction gestures and decision-making point. The DCT influence on pedagogy is in the scope of the interest as well. Moreover, the experiment analysis highlights user's needs for digital documents better interactions.

The session's interactions were documented with video cameras and the table screen records. Also, participants' feedback was collected through a custom-built questionnaire and semi-guided interviews. Figure 7 resumes main feedback collection sources.

The first part of the questionnaire offered to session participants is to fill up the System Usability Scale (SUS) (Brooke, 1996) which is composed of ten traditional items to note on a Likert Scale. The scale is a free and quick tool to measure the system usability, however it provides quite reliable results to measure usability and learnability (Sauro & Lewis, 2011)(Brooke, 2013).

Accompanying the SUS scale, earlier, for feedback collection from similar digital collaboration experiments with professionals, the 4D Collab team also included open answer questions on usability. These questions allowed us to collect more complex feedback from the AEC professionals. To stay in correlation with the previous experiment records, the same questions follow the SUS part of the questionnaire for our pedagogical experiment feedback. Additional questions on 3D, 4D and planning complete this second part. The semi-guided interviews about DCT usability and requirements, specific to the AEC, complete this part of the feedback.

Also, the questionnaire for the student teams contained parts on group reflexivity (Carter & West, 1998), a Technology Acceptance Model 3 (TAM 3) (Venkatesh & Bala, 2008) and a 4D BIM uses evaluation, however their results are not covered by this paper.

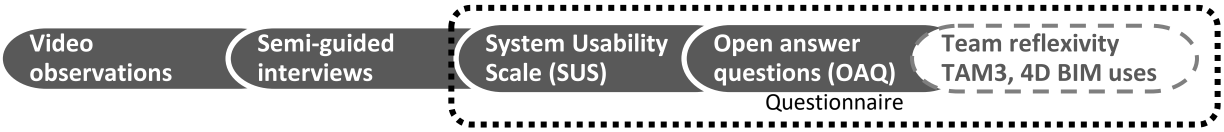


Figure 7: Summary of the feedback collection steps for the pedagogical experiment

3. Findings summary

3.1 SUS score and usability feedback

In total, we have collected a SUS from 9 users at Phase 1 in 2018, and from 29 users in 2019 at Phase 2. With two main categories of population: students and professors; and one subcategory for the students by the studies background: architects, wood and civil engineers.

The feedback for the Wood Challenge 2018 emphasized the SUS score for all users (students and professors) as a mean score of 75 points (on a scale from 0 to 100, passing range starting from 68). Thus, according to a Rating Score summarized by Bangor et al. (Bangor, Kortum, & Miller, 2009), this result would be: rated as "*good*" in adjective ratings; filling into "*acceptable*" acceptability ranges; corresponds to a letter note "C". Also, in 2018, the professors mean score of 75.83 is slightly higher than the score from the students, at 74.58, but it stays relatively close to the students and All participants (see Table 2). Regarding the study domains (subcategory), the architecture students gave a much higher score than wood structures engineers. To summarize, these scores may be interpreted that in general, 2018 users are rather pleased with Digital Collaboration Table, and find it usable and highly intuitive.

As of 2019 the mean SUS score for all users is 61.12. According to the Rating Score, this number is rated as "D", and being between "OK" and "Good" in adjective ratings. It is much lower than in 2018, and has a significant deviation. The professor result was a little higher than a year before, at 79,5, and it was very different from the student score of 56.87. The professors already had some experience with the Digital Collaboration table a year before and, even with updates, they still felt confident in the given score and positive opinion. However, in 2019 more student teams have participated at DCS than the year before, and not only those most open to innovation and digital collaboration like in 2018, which has influence on technology acceptance in general. The students also had twice as many sessions with the DCT than their predecessors, and thus had a long-term and multiple uses perspective. As before, the architecture students gave a higher score than the engineers. The scores are summarized in Table 2.

Besides the abovementioned scores by users categories, there are additional scores. Most of the participants (79% with score 69,33) have confirmed that, in general, with the DCT they could perform their actions well (with no obstacles) during collaboration sessions. As for the participants who did not say that they could execute their intentions well (score 42.5, max 47.5), they would give most often mention that session discussion is very animated and they did not have enough time (or quick enough reflexes) to quickly visualize the documents they wished to use as the discussion support. Some of them mention that they prefer to use a pen and paper for decision-making.

Besides, the active users of CAD give slightly higher SUS scores than others, but the experienced 3D model users tend to give higher scores (76) than less experienced users (55). The participants with more field experience also tend to give a higher score (76) than others with less than 2 years of experience (59,8). Despite some low SUS scores from some users, the added open questions (Section 3.2) portray a positive experience, and show again a good usability of DCT.

Table 2 Summary of SUS scores for digital collaboration table by project roles

		All participants	Students	Professors	Architects	Wood Engineers	Civil Engineers
2018	Mean Score	75	74,58	75,83	78,13	67,5	-
	Deviation	*6,96*	*8,12*	*5,2*	*4,73*	*10,60*	-
	Count	*9*	*6*	*3*	*4*	*2*	-
2019	Mean Score	61,12	56,88	79,5	59,17	56,67	53,75
	Deviation	*15,71*	*13,77*	*10,37*	*11,18*	*18,16*	*11,15*
	Count	*29*	*24*	*5*	*9*	*9*	*6*

Despite the low number of participants, we analyzed the data statistically. First, in any group larger than 8 we verified whether the score distribution was normal with two tests: Shapiro-Wilk (SW) and D'Agostino's K^2 (DAK^2). None of the scores given by architects, engineers, professors, nor all respondents together violate the normality assumption (in SW p-value ranging from 0.196 to 0.647, W from 0.94 to 0.96; in DAK^2 p-value ranging from 0.268 to 0.521, K^2 from 1.30 to 2.64). However, since normality tests are of little power on small sample sizes, for investigating the similarities and differences between the groups we did not restrict ourselves to parametric tests (T-test; whether the variance was the same or not, decided by an F-test for equal variances - always different in our case), but also carried out two non-parametric ones (Kolmogorov-Smirnov (KS) and Mann-Whitney (MW)) (Fig. 8).

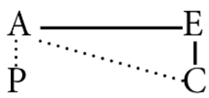


Fig. 8: the schematic representation of similar and different respondent groups by T-test, KS and MW tests: A - architects, E - engineers, C - civil engineers, P - professors. A continuous line: the scores are consistent with the hypothesis that the two groups come from the same distribution, according to all three of the tests. A disagreement between some of the tests makes it a dotted line. The absence of a line signifies that all tests reject the null hypothesis and conclude that the populations are significantly different.

The professors group, P, the highest scores, stand out from the others: their scores are statistically significantly different from those of C and E, who gave the lowest scores (p-value < 0.01 in all tests). The group that resembles P the most is the architects (A), who came out to be similar to them in the first edition of the study (p=0.580 in T-test, 0.961 in KS and 0.500 in MW test; the statistics t=0.60, F=0.33, U=5.50 respectively) and different in the second one (p-value < 0.05 in all tests, t=-3.92, F=0.80, U=1.50), bringing about mixed results when taken together (different according to T-test and MW, p<0.01, and not dissimilar according to KS, p=0.072,). The pairs A and E and C and E are consistent with the assumption that the respondents' scores come from a same population. Groups A and C are close to conforming to the similarity hypothesis but not unanimously (similar according to MW, p<0.05, U=19.00, and different according to T-test and KS, p=0.079 and 0.059, t=1.93, F=0.60).

3.2 Summary of feedback and interviews

In general, session participants (users) find the DCT very ergonomic for meetings, it unites the documents well in a single environment and allows shared views of the same document for everyone around the table. Thus, it allows better understanding, fosters collaboration, and exchanges at the meeting around the table. Also, users mention a “playful aspect” added by DCT, which creates a more informal setting for the meeting.

Regarding the document transfer at the table, users were glad to use quick wireless file drop from their laptops to the table to bring the last-minute modifications version of the document to the discussion. Some users said that digital support for the documents requires a better meeting preparation, and curiously, saw this aspect not as a disadvantage, but as an advantage which would help them to be more efficient in preparation to a meeting. However, in the beginning of meetings, when all the documents were just starting to appear on the screen, it was hard for a presentation speaker to keep everyone’s attention on the same document. Thus, to keep the focus of the users, the collaboration environment should better contain the most relevant documents to the discussion.

Visualization quality is the first of the more often mentioned benefits of the DCT, especially for 3D. Many users found a large screen to be well suited for visualization of detailed large documents (plans, sections, details, etc.), especially during review in a full-screen mode. They highlight a collective aspect of the visualization and possibility to zoom-in to view details quickly.

According to the observations, the visualization of PDF files was qualified as fluid, which was very important to review project documents. But the most emphasis was given by users to the benefits for 3D models visualization on a large screen with shared views. Indeed, according to observations a 3D model was always in the center of the discussion. In addition, users were glad to be able to share their laptop screen with a 3D or 4D model opened in their modeler (Archicad, SketchUp, Cadwork, Rhino, Navisworks) directly, without needing to export to other file formats.

Accessibility of interactions with documents is the second most often mentioned benefit of the DCT. Users have noticed progress on fluidity of actions with the latest version of the software. Users appreciate being able to zoom-in on a detail and then highlight problems with temporary or permanent annotations to explain them to others, or even to annotate simultaneously with their colleagues. A manageable 3D model navigation is also mentioned by users as one of the beneficial and essential interactions.

Many suggestions on DCT improvements were about annotation and drawing functions. More than a third of the experiment participants described the current drawing precision (line thickness, touch precision) as somewhat lackluster. Therefore, they preferred to make a double of the DCT sketch on a paper for better precision. Some suggested providing users with styluses.

Since 3D models were at the heart of most of the exchanges, many user suggestions and critiques were received about 3D visualization and navigation. For example, a few users stated that it is harder for them to understand or interact with 3D models and they prefer 2D documents. They suggest replacing 3D navigation with necessary pre-set point of view screenshots, to avoid the need to navigate through the views/model. When students were sharing their screens with 3D models (in the professional software) into the Shariiing, some have noticed delays between manipulation actions (move, zoom, rotate) and model response time. Thus, a more efficient way to share screens is to be developed and a better preparation protocol of 3D model for the session, which must be run on a performant laptop, is to be identified.

The users also highlighted a difficulty of finding the right documents and also a need to stay connected to their project cloud services, to be able to have an easy access to all the documentation directly, without downloading them into the session.

The session results and feedback formalization tool and “tasks to do” before the next meeting tool were also requested to organize better the decision-making, and document decisions in a more detailed way than 2D annotated documents.

Most of the users state that 3D visualizations are useful for decision-making on design development or value engineering. They have also agreed that 4D improves understanding of planning problems and is a useful asset for a collective decision-making on scheduling or construction strategies.

3.3 Digital Collaboration Session activities

We distinguish three main levels of interactions with DCT: visualization, manipulations, and annotations. Users may visualize 2D documents, 3D or 4D models. They may manipulate the Shariiing windows with: move, pinch, and rotate. Inside the sharing windows while visualizing the documents, “zoom” manipulation is also possible, along with annotations (drawings): temporary (disappearing), and permanent.

Also, DCS participants had access to sketching on the Shariiing background table (Fig. 6f) and notebooks and pens. Naturally, users accompany their session with discussion (verbal communication), pointing, and mimicking gestures.

The major use of the DCT was visualization (Fig.6c,d), accompanied by user discussion and pointing gestures (Fig. 5a, 6b). Model manipulations were mostly used for project presentation and to fix a point of view to annotate a solution. Sketching and annotations (Fig.6a,e,f) were used to support a solution proposition and to suggest modifications, however not every session benefited from the annotation function. Since the duration of manipulations and annotations are lower than visualization, we will count these “actions” throughout the activity.

The DCS duration depended mostly on a project design and technical solutions quality. For instance, teams presenting only 2D documents, or only 3D models, or 3D and 4D models did not show a shorter time depending on the represented document types. As a main support for decision making and discussions, participants felt more inclined to use a 3D model. They also tended to solve all the questions with only one document as a decision-making support (2D or 3D) (see Fig. 10 for sources of the shared views on the models from students’ laptops to Shariiing Advanced). Most of the time, a relevant decision would be made in the middle of a session, and would then be followed by additional suggestions on design or engineering. 4D models were used only in the beginning of the meeting to visualize construction sequence logics, but yet further discussion was supported by a 3D model due to better interactions.

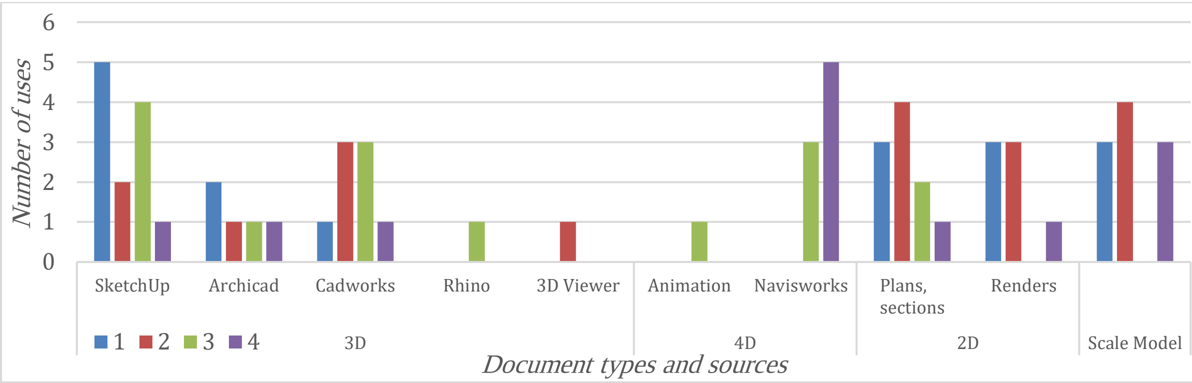


Figure 9: Information sources for Digital Collaboration Session Numbers 1-4 for Wood Challenge 2019 (shared views from laptops for 3D and 4D)

4. Conclusions

This paper summarizes the pedagogical experiment on synchronous collaboration at project review meetings with digital support (Digital Collaboration Table - DCT). The experiment context of the pedagogical exercise Wood Challenge was an opportunity to follow the collaboration of student teams and professors from the design to construction, and to assist at weekly project meetings with DCT.

Such context allowed us to evaluate DCT usability and learnability from active and frequent user perspectives in the case of a real construction project (i.e. small wooden structure). Also, the study highlighted user interactions with digital project documents during their collaboration sessions, in particular 3D and 4D model interactions. The analyzed user activities at collaboration sessions showed that 3D models are principally in the middle of the discussion, and thus must have the most fluid interactions. The DCT must provide not only the 2D annotations but also to be able to support BIM model annotations.

The Digital Collaboration Table represents a useful support for the project document’s visualization, and for the document’s manipulations and annotations. Also, it is a valuable support to more democratic collaboration of the project documents and to decision-making. However, user feedback suggests several categories for further improvements of the support and its adaptation to AEC project review. Among the key suggestions are: the need for a simple touch interface adapted to particular use cases for easier manipulation and annotation in 3D and 4D models; the need for automatic documentation of collaboration results and their integration into the BIM model structure; the need for an augmented sketching function for improved precision; the need for further integration of the table into a collaboration system connected to the cloud. These further improvements will be integrated into a prototype for a new collaborative 4D-based decision-making device by the 4D Collab research project team.

Acknowledgements

This study was developed under the patronage of “Agence Nationale de la Recherche” No.ANR-16-CE10-0006-02 (FR) and “Fonds National de la Recherche” (LU), as a part of the 4D Collab project. Authors acknowledge Wood Challenge teams for participation and “Immersion” for technical support.

References

Achten, H. H. (2002). *Requirements for Collaborative Design in Architecture*. In H. Timmermans (Ed.), *Part one: Architecture Proceedings Avegoor, the Netherlands* (Vol. 1). Ellecom. doi:http://papers.cumincad.org/data/works/att/ddssar0201.content.pdf

Bangor, A., Kortum, P., & Miller, J. (2009). Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale. *Journal of Usability Studies*, *4*(3), 114–123. Retrieved from http://uxpajournal.org/wp-content/uploads/sites/8/pdf/JUS_Bangor_May2009.pdf

Brooke, J. (1996). *SUS - A quick and dirty usability scale*. In P. W. Jordan, B. Thomas, I. L. McClelland, & B. Weerdmeester (Eds.), *Usability Evaluation in Industry* (pp. 189–194). London, UK: Taylor & Francis. Retrieved from http://hell.meiert.org/core/pdf/sus.pdf

Brooke, J. (2013). SUS: A Retrospective. *Journal of Usability Studies*, *8*(2), 29–40. Retrieved from http://www.usabilityprofessionals.org/upa_publications/jus/2013february/brooke1.html%5Cnhttp://www.usability.gov/how-to-and-tools/methods/system-usability-scale.html

Carter, S. M., & West, M. A. (1998). Reflexivity, Effectiveness, and Mental Health in BBC-TV Production Teams. *Small Group Research*, *29*(5), 583–601. doi:10.1177/1046496498295003

Kensek, K. M. (2014). *Building Information Modeling* (First edit). Abingdon: Routledge.

Oxman, R. (2008). Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium. *Design Studies*, *29*(2), 99–120. doi:10.1016/j.destud.2007.12.003

Pikas, E., Sacks, R., & Hazzan, O. (2013). Building Information Modeling Education for Construction Engineering and Management. I: Industry Requirements, State of the Art, and Gap Analysis. *Journal of Construction Engineering and Management*, *139*(11), 05013002. doi:10.1061/(ASCE)CO.1943-7862.0000765

Sauro, J., & Lewis, J. R. (2011). *When designing usability questionnaires, does it hurt to be positive?* In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI ’11* (p. 2215). New York, New York, USA: ACM Press. doi:10.1145/1978942.1979266

Staub-French, S., & Khanzode, A. (2007). 3D and 4D modeling for design and construction coordination: issues and lessons learned. *ITcon*, *Vol. 12*(September 2006), pg. 381-407. Retrieved from http://www.itcon.org/2007/26

Steinberg, G. (2012). Natural User Interfaces. *Human-Computer Interaction - INTERACT 2011*, 1. doi:10.1016/B978-0-12-382231-4.00037-X

Tory, M., Staub-French, S., Po, B. A., & Wu, F. (2008). Physical and digital artifact-mediated coordination in building design. *Computer Supported Cooperative Work*, *17*(4), 311–351. doi:10.1007/s10606-008-9077-4

Venkatesh, V., & Bala, H. (2008). Technology Acceptance Model 3 and a Research Agenda on Interventions. *Decision Sciences*, *39*(2), 273–315. doi:10.1111/j.1540-5915.2008.00192.x

Constructability of districts: capabilities of productivity and logistics big data for machine learning prediction

Dimosthenis Kifokeris[1, *], Christian Koch[1] and Yiannis Xenidis[2]
Chalmers University of Technology
Aristotle University of Thessaloniki
e-mail: dimkif@chalmers.se

Abstract

Big data, reflecting both qualitative information and quantitative material, can be used within the construction management processes of complex and large-scale building activities, such as the development of whole districts in urban areas. Such big data is probably largely focused on transport routes, productivity and site logistics portfolios. However, despite the capabilities offered by construction informatics, such data has scarcely been utilized systematically and in its full capacity for descriptive and predictive purposes. Such a systematic data utilization process can be framed through the lens of the novel construction management concept of district constructability, namely the extension of constructability into the collective level of entire districts. Constructability is here understood as the optimal use of construction knowledge and experience in planning, design, procurement, and field operations, to achieve the project objectives of time, cost and quality, and omit the gap between the as-designed and as-built project states. District constructability moves from individual projects to an overall metric for the facilitation of construction knowledge and experience implementation when undertaking large-scale construction activities (e.g. the erection of numerous buildings) for the development of entire districts; thus, it can be realized, among others, through the achievement of optimal construction productivity rates and smooth logistics operations. To combine all the aforementioned, and simultaneously fully and meaningfully exploit the capabilities that construction productivity and logistics big data may present for the assessment of district constructability, data mining can be utilized, namely the set of processes that computationally discover and "comprehend" patterns in datasets. More particularly, machine learning, here defined as the exploration of algorithms that enable computing systems to "learn" and make data-driven predictions by building a model from a sample dataset and without being explicitly programmed, can be at the methodological forefront of fully exploiting all data found in transport routes, buffer facilities, productivity rates and logistics portfolios. In this paper, the capabilities of the information structures found in the data for developing machine learning models predicting the district constructability in new large-scale urbanization activities, are examined.

Keywords: District constructability, productivity, logistics, big data, machine learning.

1. Introduction

Construction management is the research and application field that, apart from deeper systematic understanding, aim at providing the methodologies and tools implemented for the management of construction projects from their initiation until their delivery, so that their objectives of time, cost and quality are optimized (Knutson et al., 2008). As with individual projects, construction management as activity is integral in large-scale construction activities, as they are set out in long-scope urban development strategy plans for whole districts, or even towns, cities, and their metropolitan areas (see, for example, the plan of the Planning and Building Committee, 2014, for the town of Gothenburg, Sweden); such activities can include the erection of buildings (e.g. residential, offices etc.), as well as stand-alone or supporting infrastructural projects (Göteborgs Stad, 2019). Key to successful construction management, also when building districts, is the collection, understanding, and processing of relevant big data (Bilal et al., 2016; Chen & Lu, 2018); such big data can include quantitative and qualitative productivity-related indicators, such as productivity rates (Kitchin, 2014), as well as elements related to construction logistics and supply chains portfolios (Yigitcanlar et al., 2008). Within construction informatics – namely, the interdisciplinary applied field related to construction, information systems and computer science and studying the issues related to the design, processing, representation, implementation, communication and use of construction-specific information in humans and software (Turk, 2006) – methodologies and tools are explored for such meaningful utilization of big data for construction management (Turk, 2007), including data mining and machine learning (ML) (Turk, 2007; Bilal et al., 2016; Chen & Lu 2018).

Particularly, data mining is the set of processes used to discover and comprehend patterns in datasets (Bilal et al., 2016; Tan et al., 2018). ML is used for state-of-the-art data mining (Bilal et al., 2016; Witten et al., 2017), and is generally defined as the exploration of algorithms that enable computing systems to "learn", i.e. develop new algorithms linking data, and make data-driven predictions by building models from sample datasets, without being explicitly programmed (Witten et al., 2017); complementarily, it can be said that ML systems are computer systems that automatically improve through experience (Jordan & Mitchell, 2015; see also Sarkar et al., 2013; and Portugal et al., 2018). ML is frequently classified in three types: supervised, unsupervised, and hybrid. Supervised ML utilizes algorithms that are trained and validated using labeled datasets, in a context where it is assumed that the reasoning of the application domain is known (Tan et al., 2018). The task of the respective algorithm is to learn the way they should act based on real training data, validate such gained knowledge, and then apply it on new instances for predictive purposes (Portugal et al., 2018). Exemplary algorithms used in supervised ML include decision trees, decision forests, logistic regression, support vector machines, kernel methods, and Bayesian classifiers (Portugal et al., 2018). Unsupervised ML deals with unlabeled datasets having hidden patterns (Witten et al., 2017), and can be understood as "the analysis of unlabeled data under assumptions about structural properties of the data" (Jordan & Mitchell, 2015). In unsupervised ML, algorithms do not operate on a training set; the respective systems are rather presented with some data about a domain and have to develop relational models from that data "on their own", by running internal procedures (Portugal et al., 2018). Exemplary algorithms used in ML include vector quantization clustering, and generative adversarial networks (Hastie et al., 2009). Hybrid ML mixes approaches, including semi-supervised and reinforcement learning (Jordan & Mitchell 2015; Portugal et al., 2018); it is increasingly preferred in current research efforts (Portugal et al., 2018; Amasyali & El-Gohary, 2019). Even more recently, deep learning, building on the foundations of ML, has received much attention; its systems utilize gradient-based optimization algorithms to adjust parameters throughout multilayered networks, based on errors at their outputs (Jordan & Mitchell, 2015).

As noted earlier for the case of large-scale construction activities, the big data to be used within construction management can be both qualitative (e.g. lessons-learned databases), and quantitative (e.g. cost and time overheads) (Chen & Lu, 2018; Yeung et al., 2018). However, and despite the capabilities offered by construction informatics, it has scarcely been utilized systematically and in its full capacity for descriptive and predictive purposes (Bilal et al., 2016); it is mostly used either in a simple informatory manner (Bilal et al., 2016), or for more narrow applications (Bilal et al. 2016; Tixier et al., 2016). Empirical knowledge is still the main driver of state-of-art construction management, even when aided by cutting-edge methodologies and tools utilized within construction informatics, and especially

ML and its aforementioned variants (Bilal et al. 2016; Tixier et al., 2016). Construction managers still prefer to mainly use hands-on experience; but while tacit experience is essential, a more holistic data utilization could enhance the managers' decision-making and action-taking (Kumar & Reinartz, 2018).

Such a ML-aided holistic data utilization for construction management, can prove essential in the messy environment of large-scale construction activities, like the development of entire districts. This can be even more crucial in cases of rapid urbanization; such an intensive activity and its associated complex processes, especially within densely populated areas, may result in several construction management issues, like productivity- and logistics-related ones (e.g. delayed deliveries, complicated supply chain coordination, and low on-site productivity) (Dubois et al., 2017). But to reach such a meaningful and systematic utilization with practical and useful results, the relative contextual framework must be devised, the associated types and orders of datasets must be identified, and the suitable technical aspects (e.g. the ML algorithms) of the model leading to the realization of the framework must be investigated, tested and verified. The aim of this paper is to devise a conceptual framework, for the exploitation of big data to build ML models acting as decision-making and action-taking helpers for construction managers operating within large-scale urban activities (culminated in the case of whole district construction). In the second section of the paper, the introduction of the concept of district constructability will act as the contextualization of the framework. In the third section, forms of big data generated in district development, and especially the ones related to productivity and construction logistics, will be investigated in terms of their capabilities and suitability for use within ML models appraising district constructability. In the fourth section, early considerations for the realization of the conceptual framework will be showcased. Following will be the conclusions and recommendations for future work.

2. Context: district constructability

Constructability is "the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (Construction Industry Institute, 1986). It is a crucial aspect of optimal construction management, and it encompasses buildability ("the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building" (Construction Industry Research and Information Association, 1983) as its design- and early construction-related aspect. Constructability, also including early contractor involvement, is implemented through the whole initiation, execution, and delivery project lifecycle phases to optimize the project's performance objectives of time, cost, and quality (Construction Industry Institute, 1986), as well as client satisfaction (Poon et al., 1999). Such an implementation is achieved with constructability programs, namely "the application of a disciplined, systematic optimization of construction-related aspects of a project during the planning, design, procurement, construction, test, and start-up phases by knowledgeable, experienced construction personnel who are part of a project team" (Construction Management Committee of the American Association of Civil Engineers, 1991). For the realization of constructability programs, several methodological and application frameworks have been integrated with constructability, such as – indicatively – planning and operations performance evaluation, hybrid value engineering, knowledge management, cost/benefit analysis, total quality management, object-oriented analysis, total building performance, regression analysis (Kifokeris & Xenidis, 2017), and technical project risk analysis (Kifokeris & Xenidis, 2019). Furthermore, numerous related cognitive, mathematical, programming, and software methodologies and tools have been developed to appraise and/or assess constructability in terms of quantitative and qualitative project features' assessment, schedule-cost-quality management and decision-making, program review, information feedback, and knowledge management and dissemination (Kifokeris & Xenidis, 2017), including, among others, diverse ML models (Skibniewski et al., 1997; Ugwu et al., 2005; Le et al., 2018; Kifokeris & Xenidis, 2019).

Among others, important constructability aspects are a holistic view on logistics (including, but not limited to, supply chain integration, on-site resources flow management, and close cooperation of the related actors), and the optimization of the productivity of the whole project lifecycle, and especially during on-site operations (Kifokeris & Xenidis, 2017). Even for large-scale construction activities, such as the development of entire urban districts, constructability of individual projects (e.g. high-rise buildings) can be realized, among others, through the achievement of optimal construction productivity rates and smooth logistics operations (Kifokeris, 2018). In conjunction with that, the overall performance of construction activities in the district level can be contextualized accordingly and appraised in terms of optimized productivity and smooth logistics operations – as reflected in the relative big data generated in each case – which centrally include quantitative and qualitative productivity-related indicators (such as productivity rates (Kitchin, 2014)) and elements related to construction logistics and supply chains portfolios (Yigitcanlar et al., 2008). Considering the two aforementioned points and by exploiting (a) the direct connection of constructability to the overall project objectives rather than narrow applications, (b) its affiliation with construction knowledge and experience implementation, and (c) the capabilities of construction informatics (and especially ML) in extracting and processing productivity- and logistics-related data, a novel predicting ML system aiming at holistically enhancing the decision-making, action-taking and knowledge communication of construction managers affiliated with the urban development of entire districts, can be formulated.

To capitalize on the points made above and create a contextualization for the previously mentioned predicting system, we hereby propose the concept of district constructability. District constructability extends constructability from individual projects to an overall, collective metric for the facilitation of construction knowledge and experience implementation when undertaking large-scale construction activities (e.g. the erection of numerous buildings) for the development of entire districts, thus acting as a qualitative performance indicator for urban development. Central factors in the appraisal of district constructability are qualitative and quantitative indices and metrics connected to on-site construction productivity and construction logistics operations on the district level. Therefore, in the abovementioned potential predicting system, district constructability can provide the context of its conceptualization and realization, since in the core of this system there can be a model for the prediction of the way construction productivity rates and logistics and supply chain issues in the district level can affect the associated district constructability.

3. Big data for district constructability appraisal

Following the contextualization of the previous section, forms of big data generated in district development, and especially the ones related to productivity and construction logistics, will be investigated in terms of their capabilities and suitability for use within ML models appraising district constructability. As the basis for this investigation, the data found in the productivity report "Produktivitetsläget i svenskt byggande 2014" [Productivity status in Swedish construction 2014] (Koch & Lundholm, 2018) – based on the work by Josephson (2013) – was used. The aforementioned report adopts the metrics of cost (SEK, Swedish crowns) and work hours per square meter of total gross area, for the measurement of productivity for different building types. In addition, logistics problems are identified and qualitatively assessed on a five-point Likert scale. It is assumed that project output depends on the relevant conditions (such as the performance of the project organization) as input, and then the production process takes place and "causes" costs and working time (namely, productivity), as well as logistics issues, as the output. Significant stakeholders are identified for each project, such as the clients, the contractors, and the suppliers.

The data in "Produktivitetsläget i svenskt byggande 2014" was collected through telephone interviews supported by questionnaires. In this way, answers are based on the respondent's own perspective (Koch & Lundholm, 2018). Construction projects encompassed in the survey are primarily premises. These include daycare centres, schools, office buildings, administrative buildings, sports and recreation facilities, hospitals and elderly care centres, church buildings, nursing homes, stores, industrial properties, and group-built family houses. In each individual project, the client's project manager and the contractor's site manager answered the relevant questionnaires, during the period of October to November 2014. The questions covered project aspects, such as the relevant processes, organization, costs, time, work progress, and team performance, and their number was limited. In the respective questionnaires, the clients received 23 questions and the site managers 21. The surveys were sent to 1000 individuals, with 580 valid responses (58% overall answering rate). The survey was answered by 324 contractor representatives (72% answering rate), and 256 clients (62% answering rate).

The relevant statistics are interesting in revealing the most central existing issues regarding productivity, construction logistics and supply chain management in the sites investigated; the issues of on-site congestion, transportation challenges and storage bottlenecks, are experienced by site managers at around 40% of the studied projects (Koch & Lundholm, 2018). Congestion is thus recurrent to an extent, yet an exception compared to 60% of the sites not reporting it. Some of the districts corresponding to site managers reporting congestion were situated in Stockholm and Malmö; however, and surprisingly enough, congestion was also evident in much less populated towns. In total, the central productivity and logistics issues concerned ten districts ("kvartärer") or and four single or multi-project areas having similar development needs (e.g. brownfields).

In the district development cases, the productivity rates and the logistics and supply chain issues were calculated and appraised, respectively, in the ways mentioned above. Logistics and supply chain issues primarily pertained to the good cooperation of the project group regarding on-site supply chain tasks, disturbances in the relative flows, on-site congestion, keeping of the delivery timetable, difficulties in material and equipment transportation and storage due to on-site narrow spaces, limitations in the construction production and logistics preparation, the extent of available staffing for the construction works (recognized as a risk source for constructability in Kifokeris & Xenidis, 2018, and therefore potentially extensible to the case of district constructability), and the informed selection of the material and equipment suppliers (Koch & Lundholm, 2018).

The data found in the above also needs to be further complemented with more data found in logistics portfolios and productivity studies of construction projects, and can then be utilized as a basis for a translation into independent variables that suit predictive ML systems, e.g. ones using support vector machines and/or support vector regression for classification or regression, respectively, through supervised ML. The productivity rates can be translated into continuous numerical variables, having as benchmarks median productivity rate values in relation to e.g. the size, number and type of the individual projects constructed during the whole district development activities. In addition, the logistics and supply chain management issues appraised through the Likert scales can be translated into multinomial categorical variables, or processed into binomial variables 1 or 0, for "yes" or "no" for binary classification problems.

To properly train the respective ML models, district constructability should also be translated into the dependent variable. Evaluation of district constructability is at present mostly built on experiential knowledge supplemented by some modeling, according to interviews conducted by the authors. However, in the relevant literature, there has not been yet, to the best of the authors' knowledge, a meaningful representation of constructability as a continuous variable – apart from some early conceptual attempts like the one of Yu & Skibniewski, 1999. Therefore, it may be sensible to base the representation of district constructability on efforts treating constructability itself as a discrete variable (e.g. on the binomial constructability variable in Kifokeris & Xenidis, 2019). As district constructability is, both in itself and as an object of machine learning modelling, a hereby introduced new concept, it may be difficult to properly define a continuous domain for its numerical values, along with all the associated thresholds and benchmarks. Therefore, a multinomial representation (e.g. via a three- or five-point Likert scale, or via whole-number percentages) of district constructability could be more informative and in line with the current related research trends.

To sum up these insights, in Table 1 (see next page) there is an exposition of the exemplary independent variables that can be potentially derived from big data found in studies on productivity, logistics, and supply chain management, as well as the translation of district constructability into a dependent variable. Such a list of variables can be enrichened with yet more relative elements generated within similar research and practical studies, like, for example, production flow inventories, descriptions of construction site spatial and schedule clashes, number of reworks, material quantity problems, optimal vehicle rounds, district disturbances, and the existence and proper function of buffer facilities for vehicles and goods.

Table 1: Exemplary independent and dependent variables for district constructability appraisal, as derived from Koch & Lundholm (2018)

Independent variables	Type	Example of value
Productivity rate	Continuous	0,1 (%)
Level of project group cooperation for on-site supply chain tasks	Discrete multinomial	{1,…,5}
Flow disturbance	Discrete multinomial	{1,…,5}
On-site congestion	Discrete multinomial	{1,…,5}
Keeping of delivery timetable	Discrete multinomial	{1,…,5}
Difficulties in material and equipment transportation and storage	Discrete multinomial	{1,…,5}
Limited construction production and logistics processes preparation	Discrete multinomial	{1,…,5}
Enough workforce for optimal undertaking of construction tasks	Discrete multinomial	{1,…,5}
Informed selection of material and equipment suppliers	Discrete multinomial	{1,…,5}
Dependent variable	**Type**	**Example of value**
District constructability	Discrete multinomial	{1,…,5}

In addition, indicators and metrics of the infrastructure in and around the district (e.g. access routes, points of entry, traffic diversion and/or emergency roads) should be considered, for a more holistic representation of real situations in district development.

4. Modelling aspects of the conceptual framework

After the relative contextualization with the introduction of district constructability, and the investigation of the capabilities of forms of productivity- and logistics-related big data generated in district development for use within a ML model appraising district constructability, the early conceptual steps and considerations for the actual formulation of such a model are given in Figure 1 (see next page).

What is showcased in Figure 1 can be furtherly explained in the following:

Step 1. Data collection. For a large number of building projects that are part of the ongoing entire district development, the data suppliers will provide quantitative and qualititative construction productivity and logistics data (e.g. site productivity rates, production flow inventories, descriptions of construction site spatial and schedule clashes, material quantity problems, material and equipment transport routes and bottlenecks, indicators about buffer facilities). In addition, they will supply a qualitative district constructability labelling of the respective districts (e.g. using a five-point Likert scale). The interpretation of the qualitative labels as levels of district constructability achievement, can be obtained through interviews along with the data providers.

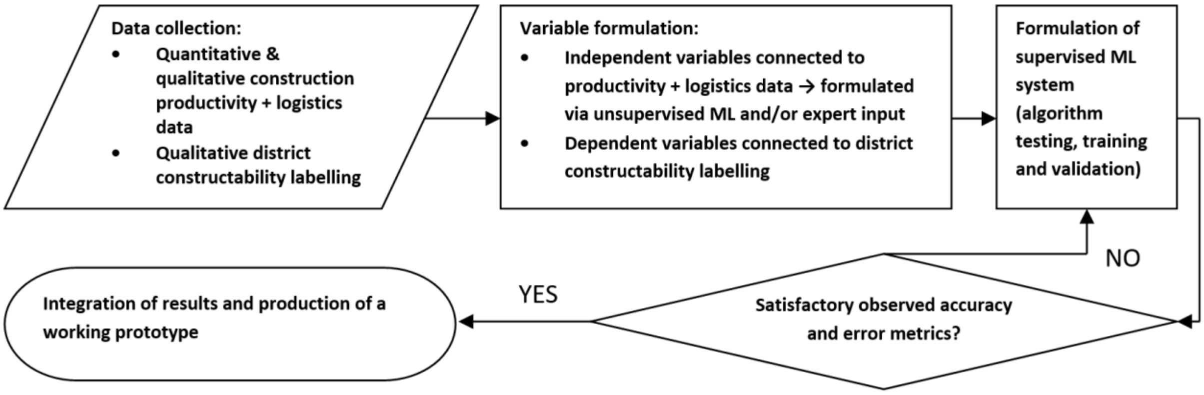


Figure 1: Explanatory simplified flowchart describing the conceptual framework

Step 2. Variable formulation. Independent variables: Depending on the form of the construction productivity and logistics data, meaningful independent variables (e.g. "Number of reworks") measured through the values of the collected data, will be produced either through unsupervised ML techniques (e.g. vector quantization, linguistic clustering), or qualitative techniques relying on expert input (e.g. brainstorming). Dependent variables: These will be the district constructability achievement levels, and can act, for example, as multinomial discrete classification variables.

Step 3. System formulation. A ML system trained and validated with the collected data, in the way it is expressed through the independent and dependent variables previously defined, will be formulated. A possibility is to choose a multinomial classification supervised ML scheme to be trained and validated, as it can be derived from the data form and amount, and the variables' type and number. This choice can be specified as a result of multiple experiments conducted within a suitable platform (like the Waikato Environment for Knowledge Analysis – WEKA) (Witten et al., 2017), with numerous algorithms, such as variations of the support vector machines and the random forest algorithms. Given the pre-study of the previous section on the possible representation of the exemplary variables, such a multinomial classification supervised ML scheme can operate with algorithms like naive Bayes classifiers, decision trees, random forests, k-nearest neighbors, support vector machines (SVM), and types of artificial neural networks, as they are considered suitable for such classification problems (Witten et al., 2017).

Error and observed accuracy metrics can be used during each training and validation iteration of the respective algorithms, to determine the actual correctness of the algorithmic results. Among such error metrics are included the Cohen's kappa, mean absolute error, true positive rate, false positive rate, precision, recall, F-measure (Witten et al., 2017), and the Matthews correlation coefficient (Chicco, 2017). When the observed accuracy rates after the training and validation of the respective algorithm are sufficiently high and/or satisfactory, and at the same time the aforementioned metrics are within thresholds characterized as good or optimal (Witten et al., 2017), there can generally be little to no room for further optimization for the respective modelling with the current dataset t has been presented with (Witten et al., 2017).

Auxiliary mathematical, methodological and software tools may be utilized to various extents within Steps 1-3, such as (a) non-negative matrix factorization for data normalization and pre-processing (Steps 1-2), (b) multi-input Analytical Hierarchy Process (AHP), for variable labelling (Step 2), (b) the "kernel trick", to aid in the non-linear function of certain supervised ML algorithms, if elected (Step 3), (d) n-fold cross-validation, for the simultaneous training and validation of certain supervised ML algorithms, if elected (Step 3), (e) the WEKA platform (Step 3), (f) Surprise Scikit (Steps 2-3), and (g) the programming language Python (Steps 2-3).

Step 4. Integration of results and production of a working prototype. The ML system can be integrated as a working prototype within construction management plans in the district level, for the verification of its predicting results – namely, the appraisal of the level of district constructability during the development of new districts, given the values of the productivity- and logistics-related metrics utilized as independent variables, as those values are generated in the course of the district development. This may take place through suitable programming routines and/or graphical user interfaces (such as PyQt, featured in the Anaconda platform).

Such a novel methodological framework and subsequent modelling can not only break ground with the proposition and appraisal of a new concept connected to urban development in the district level, but can furtherly strengthen the placement of ML within construction informatics, for the benefit of construction managers and related disciplines.

5. Conclusions

The urban development of entire districts represents a wide array of interconnected construction activities through multiple individual building and infrastructural projects; it can also generate big data primarily culminated in metrics such as productivity rates and identified issues related to on-site logistics and supply chain management. Apart from their individual exploitation for informatory reasons, these points of data can also be used as a means to measure yet more holistic metrics, which can provide construction managers (and other key stakeholders) with a higher-level overview of the district development process, thus helping in more well-founded decision-making and action-taking.

Models utilizing ML algorithms and miscellaneous methodological, mathematical and programming tools, can provide the framework for such a meaningful understanding, processing and exploitation of the aforementioned big data for descriptive and predictive purposes, as long as there are suitable concepts to contextualize this implementation in the construction and district development sector. Such a concept can be found in the hereby introduced notion of district constructability, which is an extension of the construction management concept of constructability from the level of individual projects to an overall, collective metric for the facilitation of construction knowledge and experience implementation when undertaking large-scale construction activities (e.g. the erection of numerous buildings) for the development of entire districts; thus, district constructability can acting as a qualitative performance indicator for urban development.

Qualitative and quantitative indices and metrics connected to on-site construction productivity and construction logistics operations on the district level can be used for the appraisal of district constructability. So, for the culmination of a relative ML model, independent variables can be generated from such metrics, and then computationally correlated with a dependent variable representing district constructability. Such independent variables can include, among others, the level of project group cooperation regarding on-site supply chain tasks, flow disturbances, on-site congestion, keeping of the delivery timetable, material and equipment transportation and storage difficulties, limitations in the construction production and logistics preparation, construction staff availability, material and equipment suppliers selection, optimal vehicle rounds, the function of buffer facilities, the level of disturbance due to the on-site construction and transportation activities, production flow inventories, descriptions of on-site spatial and schedule clashes, number of reworks, and material quantity problems.

A recommendation for further research is the actual realization of Steps 1 and 2 of the presented framework through access in the relative databases given by the interested stakeholders. Concurrently, the study of and experimentation with ML algorithms on a suitable platform should be undertaken, to prepare for the realization of Step 3. ML is a field that can present a wealth of opportunities for the development of solutions within the construction sector and construction management specifically, and even more in high/profile activities such as the development of entire urban districts.

References

Amasyali, K., & El-Gohary, N. (2019). Predicting Energy Consumption of Office Buildings: A Hybrid Machine Learning-Based Approach. In: Mutis, I., & Hartmann, T. (Eds.). Advances in Informatics and Computing in Civil and Construction Engineering: Proceedings of the 35th CIB W78 2018 Conference: IT in Design, Construction, and Management. (pp. 695-700). Cham: Springer Nature.

Bilal, M., Oyedele, L. O., Qadir, J., Munir, K., Ajayi, S. O., Akinade, O. O., Owolabi, H. A., Alaka, H. A., & Pasha, M. (2016). Big Data in the construction industry: A review of present status, opportunities, and future trends. Advanced Engineering Informatics, 30(3), 500-521.

Chen, X., & Lu, W. S. (2018). Scenarios for Applying Big Data in Boosting Construction: A Review. In: Chau, K. W., Chan, I. Y. S., Lu, W., & Webster, C. (Eds.). Proceedings of the 21st International Symposium on Advancement of Construction Management and Real Estate (pp. 1299-1306). Singapore: Springer Nature.

Chicco, D. (2017). Ten quick tips for machine learning in computational biology. BioData Mining, 10(35), 1-17.

Construction Industry Institute (CII) (1986). Constructability: A primer. Publication 3-1. Austin: University of Texas at Austin.

Construction Industry Research and Information Association (CIRIA) (1983). Buildability: An assessment. London: CIRIA Publications.

Construction Management Committee of the American Association of Civil Engineers (ASCE) (1991). Constructability and Constructability programs: White Paper. Journal of Construction Engineering and Management, 67–89.

Dubois, A. Hulthén, K, & Sundquist, V. (2017). Organising logistics and transport activities in construction. The International Journal of Logistics Management, 30(2), 620-640.

Göteborgs Stad (2019). Stadsutveckling Göteborg. Retrieved from https://stadsutveckling.goteborg.se/tidslinje/

Hastie, T., Tibshirani, R., & Friedman, J. (2009). The Elements of Statistical Learning: Data mining, Inference, and Prediction. New York: Springer.

Jordan, M. I., & Mitchell, T. M. (2015). Machine learning: Trends, perspectives, and prospects. Science, 349(6245), 255-260.

Josephson, P. E. (2013). Produktivitetsläget i svenskt byggande 2013, nybyggnad flerbostadshus och kontor. Stockholm: Sveriges Byggindustrier.

Kifokeris, D. (2018). Risk-based Constructability Assessment in Civil Engineering Projects. (Doctoral dissertation, Aristotle University of Thessaloniki, Thessaloniki, Greece). Retrieved from http://ikee.lib.auth.gr/record/301230/files/GRI-2018-23059.pdf

Kifokeris, D., & Xenidis, Y. (2017). Constructability: outline of past, present, and future research. Journal of Construction Engineering and Management, 143(8), 04017035-1 – 04017035-13.

Kifokeris, D., & Xenidis, Y. (2018). Application of linguistic clustering to define sources of risk in technical projects. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 4(1), 04017031 – 1-04017031-13.

Kifokeris, D., & Xenidis, Y. (2019). Risk source-based constructability appraisal using supervised machine learning. Automation in Construction, 104, 341-359.

Kitchin, R. (2014). The real-time city? Big data and smart urbanism. GeoJournal, 79(1).

Knutson, K., Schexnayder, C. J., Fiori, C. M., & Mayo, R. (2008). Construction Management Fundamentals (2nd ed). New York: McGraw-Hill Education.

Koch, C., & Lundholm, M. (2018). Produktivitetsläget i svenskt byggande 2014. Lokaler, Grupphus och Anläggning. Stockholm: Sveriges Byggindustrier.

Kumar, V., & Reinartz, W. (2018). Data Mining. In: Customer Relationship Management. Berlin, Heidelberg: Springer Texts in Business and Economics.

Le, T., Le, C., Jeong, H. D., Gilbert, S. B., & Chukharev-Hudilainen, E. (2018). Requirement Text Detection from Contract Packages to Support Project Definition Determination. In: Advances in Informatics and Computing in Civil and Construction Engineering: Proceedings of the 35th CIB W78 2018 Conference: IT in Design, Construction, and Management. (p. 569-576). Cham: Springer Nature.

Planning and Building Committee (2014). Development Strategy Göteborg 2035. Gothenburg: Göteborgs Stad.

Poon, J., Potts, K., & Cooper, P. (1999). Development of a new best practice model for building projects. In: Hughes, W. (Ed.). Proc., 15th Annual ARCOM Conference (pp. 705-714). Liverpool: Association of Researchers in Construction Management Publications.

Portugal, I., Alencar, P., & Cowan, D. (2018). The Use of Machine Learning Algorithms in Recommender Systems: A Systematic Review. Expert Systems With Applications, 97(1), 205-227.

Sarkar, D., Bali R., & Sharma, T. (2013). Practical Machine Learning with Python. New York: Apress.

Skibniewski, M., Arciszewski, T., & Lueprasert, K. (1997). Constructability analysis: machine learning approach. Journal of Computing in Civil Engineering, 11(1), 8-16.

Tan, P. N., Steinbach, M., Karpatne, A., & Kumar, V. (2018). Introduction to data mining (2nd ed.). Boston: Pearson.

Tixier, A. J. P., Hallowell, M. R., Rajagopalan, B., & Bowman, D. (2016). Application of machine learning to construction injury prediction. Automation in Construction, 69, 102-114.

Turk, Ž. (2006). Construction informatics: Definition and ontology. Advanced Engineering Informatics, 20(2), 187-199.

Turk, Ž. (2007). Construction Informatics in European Research: Topics and Agendas. Journal of Computing in Civil Engineering, 21(3), 211-219.

Ugwu, O. O., Anumba, C. J., & Thorpe, A. (2005). Ontological foundations for agent support in constructability assessment of steel structures – a case study. Automation in Construction, 14(1), 99-114.

Witten, I. H., Frank, E., Hall, M. A., & Pal, C. J. (2017). Data mining: practical machine learning tools and techniques (4th ed). Cambridge, Massachusetts: Morgan Kaufmann, Elsevier.

Yeung, C. L., Wang, W. M., Cheung, C. F., Tsui, E., Setchi, R., & Lee, R. W. B. (2018). Computational narrative mapping for the acquisition and representation of lessons learned knowledge. Engineering Applications of Artificial Intelligence, 71, 190-209. https://doi.org/10.1016/j.engappai.2018.02.011

Yigitcanlar, T., O'Connor, K., & Westerman, C. (2008). The making of knowledge cities: Melbourne's knowledge-based urban development experience. Cities, 25(2), 63-72.

Yu, W., & Skibniewski, M. J. (1999). Quantitative constructability analysis with a neuro-fuzzy knowledge-based multi-criterion decision support system. Automation in Construction, 8(5), 553-565.

Structural Design in early Planning Phases using Engineering Expert Knowledge and Intelligent Substitution Models

M. Schnellenbach-Held[1,*] and D. Steiner[1]
Institute for Structural Concrete, University of Duisburg-Essen, Essen, Germany
email: m.schnellenbach-held@uni-due.de

Abstract

An early integration of the highly complex decision-making processes for structural design requires the implementation of applicable engineering expertise. For this purpose, intelligent substitution models for the structural preliminary design are developed. These are based on development level dependent structural expert knowledge. The formulation of the included engineering knowledge with Fuzzy Logic methods allows the use of linguistic variables and understandable expert rules. For the development of associated inference systems and the resulting substitution models, the basic knowledge bases are generated through parameter studies. Complementary mapping processes are supplemented by continuing optimization tasks. Considering the typical design progression of the structural preliminary design, a specialized level system is developed and related information requirements are analyzed. The substitution models contain the knowledge related inference systems and include extensive applicable engineering knowledge. Formalization of the involved engineering expertise is realized through functional fuzzy models that contain fuzzy parameters and rule-based inference systems. The resulting substitution models emulate the engineering decisions for assessments and suggestions of applicable structures. The resulting system enables the realization of a decision-making assistance for structural design in early stages and for modification processes. As a result, designers are provided with an early support of complex design decisions allowing high efficiency gains. Included are the recommendations for feasible and economically optimized designs as well as their preliminary dimensioning. Consequently, the intelligent substitution models include the necessary level dependent engineering expertise. Thus, an appropriate decision support is integrated into the design process. The resulting consideration of the structural planning perspective in early phases enables a successful design of buildings and an improved planning progression. Finally, the provided support of the design in early planning phases enables a harmonization and an efficiency enhancement of the design process. For demonstration of the enhanced planning process, the design of a fictional building model is performed with illustration of the decision-making assistance by the developed substitution models. Two common design progressions are presented that are based on different planning perspectives. For the structural engineering point of view, the typical process is executed according to the developed level system. Another advanced architectural perspective entails an alternative development level system. The application of the substitution models for different approaches is enabled through adaptive detailing concepts that allow assignments of the structural design levels to alternating systems.

Keywords: Formalization of engineering knowledge, decision support using expert knowledge, fuzzy inference systems, preliminary structural design, building design scenarios.

1. Introduction

In early phases of the building planning process, the structural concept significantly influences the quality of a design (Zhang et al, 2018) and the factors time and costs of an architecture (Kim et al, 2015). As creative and functional aspects are the essential basis for the common design procedure, only few and rough planning principles are allowed for structural evaluations. Thus, assurance of applicability and efficiency of a building design requires the early integration of the structural engineering perspective in the planning process and the following collaboration of all involved planners (Schnellenbach-Held and Hartmann, 2003; Oh et al, 2015; El-Diraby et al, 2017). In the resulting interdisciplinary design process, simplified formulae and especially the engineering experience of the structural engineers are usable for design assessments that are based on few and rough boundary conditions in early phases (Schnellenbach-Held and Albert, 2003). The appropriate engineering expert knowledge is related to different development levels (Maier et al, 2017) and necessitates an applicable formalization approach (Steiner, 2018) as well as extensive structural analyses and simulations (Liu et al, 2018). Using the resulting knowledge and related evaluation tools, the complex task of structural decision-making support and an associated interdisciplinarity are enabled in early planning phases (Schnellenbach-Held et al, 2006). For this purpose, intelligent substitution models are developed that are based on development-level dependent fuzzy knowledge bases for structural preliminary design (Schnellenbach-Held and Steiner, 2018). Exemplary progressions of the enhanced planning process are demonstrated with the aid of illustrative building design scenarios.

2. Structural design in early planning phases

The integration of the structural engineering perspective in early phases of the building planning process is realized through intelligent substitution models for the structural preliminary design (pre-design). For this purpose, representative adaptive levels of development (ALoD) are identified for the structural assessments of building models. Applicable engineering expert knowledge for the different design states is formalized using methods of Fuzzy Logic. Parameter studies and optimization tasks are performed to generate structural information for fuzzy knowledge bases to include the engineering experience. The simulation of associated decision-making processes is realized through inference systems that form the basis for the intelligent substitution models. The resulting systems enable the decision support for structural pre-design through the integration of the structural engineering perspective in early planning phases of building design. Thus, an optimization of the design process is facilitated through harmonization effects and efficiency increases (Steiner and Schnellenbach-Held, 2018).

2.1 Adaptive levels of development for structural pre-design

For the consideration of the structural design requirements, a specialized detailing system (see figure 1) is developed that contains five adaptive levels of development (ALoDs). According to the common design process from structural engineering perspective, the basic understanding and related parameters for load bearing systems are included. Additionally, transfer functions are introduced for the determination of complementary building model information that are realized as the intelligent substitution models. They evaluate the required parameters for the following design status based on the limited data of the lower ALoD. The building model development according to the ALoD system is demonstrated in the structural design scenario. As starting point for the design progression, the “ALoD 0” is defined as blackbox that contains global information as well as environmental and boundary conditions. The following architectural development of a room plan leads to the “ALoD 1” that involves the geometrical parameters of the building components and is comparable to the physical building model. Based on the subsequent positioning, the typical idealization of the load bearing elements is introduced in the “ALoD 2a” that resembles an analytical model. The common positions represent the basis for the evaluation and the design of structures that is realized through engineering expert knowledge according to conventional calculation approaches. As alternative to the architectural specifications, the substitution model "grid" performs an estimation for the arrangement of optimized components based on analyzed structural design knowledge. The suitability of different construction types for the structural positions is content of the "ALoD 2b" and determined by the substitution model "possibility". Thus, the engineering experience based expert assessment is simulated, allowing a support of the decision-making process for the preliminary design and the change management of building models. For the selected construction, the characteristic structural parameters are determined through the substitution model "pre-design". By complementation of the conclusive specifications that are content to the final "ALoD 3", the preliminary design of the structural elements is finished and further analyses of the building model are allowed (Steiner and Schnellenbach-Held, 2018).

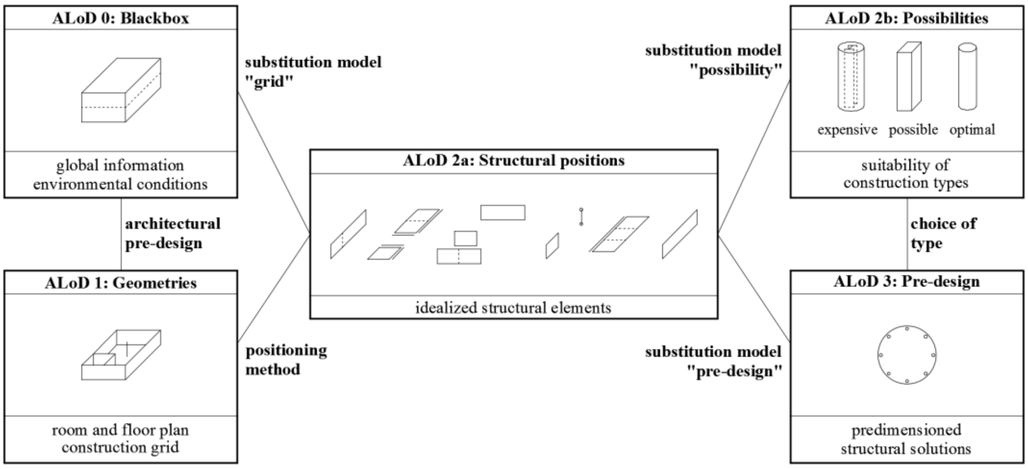


Figure 1: Development levels for structural design based on Steiner and Schnellenbach-Held 2018

2.2 Intelligent substitution models for structural pre-design

The developed intelligent substitution models for structural assessments and preliminary design are based on the application of associated engineering experience. This expertise is expressed using Fuzzy Logic methods, so that the utilization of expert knowledge and rule-based inference systems is allowed. Using such systems, the human decision-making mechanisms and reasoning competences are imitable even under most complex conditions, as extraordinary generalization abilities are featured (Steiner and Schnellenbach-Held, 2017). Following the formalization approach, ALoD-dependent fuzzy knowledge bases are developed for the inclusion of applicable engineering expert knowledge. The included assessment and design of load bearing elements is based on binding codes and directive standards as well as the knowledge, experience and competence in the field of structural engineering. Being phrased in the Modus Ponens "if premise (lower ALoD), then conclusion (higher ALoD)", the resulting rule bases are transparent and easy to understand (see table 1). The related decision-making processes that enable the knowledge-based evaluation of model parameters for the design development, are realized as functional TSK fuzzy inference systems (Steiner and Schnellenbach-Held, 2018).

For the typical idealized structural elements (ALoD 2a), parameter studies are performed at the related calculation models to generate the expert knowledge. Adequate value boundaries and parameter samplings of the studies are determined through common engineering experience. The determination of the usability (ALoD 2b) and the design values (ALoD 3) of the elements is based on the satisfaction of the required limit states according to Eurocode. If all design criteria are satisfied, the plannable structure is qualified as "possible". Otherwise, the assessment of infringing elements is formulated as "not realizable". A further refinement of the possibility is based on additional expert knowledge for structural assessments. To meet the large number of possible structures for certain boundary conditions, the search for a minimized approximate realization effort is performed by optimization tasks. For the optima, the expression as expert rules is practicable and allows a verification with common engineering experience. Subsequently, a comparison basis for design choices and change management is established through update of the expert assessment (ALoD 2b) with the complementary knowledge. The estimation of construction grids featuring applicable and optimized structural elements (ALoD 2a) is based on superordinate rules that are identified through analyses of the resulting engineering assessment knowledge. Finally, the rule bases are derived from the incrementally approximated functions for structural design forming the inference systems of the resulting substitution models. For the building design process, they allow a reliable decision support that enables the integration of the structural engineering perspective in early phases (Steiner, 2018).

Table 1: Exemplary rule for the inference systems of the substitution models

Rule		***Parameter***		***Fuzzy set***	***Crisp value***	***ALoD***
IF		*Position*	=		*Single -span slab*	*ALoD 2a*
	AND	*Useful load*	=	*“small”*	*2,00 kN/m²*	*ALoD 2a*
	AND	*Height*	=	*“small”*	*0,20 m*	*ALoD 2a*
	AND	*Length*	=	*“small”*	*3,00 m*	*ALoD 2a*
THEN		*Possibility*	=	*“optimal ”*	*1,0 -*	*ALoD 2b*
	AND	*Concrete class*	=		*C20: smallest possible*	*ALoD 3*
	AND	*Reinforcement*	=	*“small”*	*6,79 kg/m*	*ALoD 3*

3. Scenarios for exemplary enhanced design processes

The support of the building design process is demonstrated with the aid of illustrative exemplary simple scenarios. For this purpose, the design of a fictional building model is performed with illustration of the decision-making assistance by the developed substitution models. Two common design progressions are represented that are based on different planning perspectives. For structural engineering, the typical process is executed according to the developed ALoD-system (Schnellenbach-Held and Steiner, 2018). Another point of view results from an advanced architectural perspective that entails an alternative development level system (Abualdenien and Borrmann, 2019). The application of the substitution models for the different BDL approach is enabled through adaptivity of the ALoD concept that allows an assignment of the structural design levels to alternating systems. Additionally, the realized decision support includes the integration of suggested options (Mattern and König, 2018) to improve the support acceptance and to allow further comparative analyses like energy efficiency calculations (Geyer et al, 2018; Harter et al, 2018). For involved communication aspects (Zahedi and Petzold, 2018), the data flow of the model parameters for structural design purposes is outlined. The resulting demonstrations show the enhancement of multidisciplinary building design assessments through engineering expert knowledge and the developed intelligent substitution models.

3.1 Basic structural design scenario

The scenario starts with the specification of a blackbox in ALoD 0 that is represented by the external total lengths and height as well as the shape of the building. Additional data is requested regarding the global information and environmental conditions. The significant parameters are the usage category for the useful load estimation, the soil condition for foundation assessments and the global location for further influences like earthquakes and exposures like see salt. In this stage, different dimensions and building shapes might be considered as options that are specified by participants like the architect or the building owner. Based on the blackbox, two procedures are feasible for the determination of the building elements. In the common design process, the architect provides a floor plan with complete geometrical specifications. Apart from that, a construction grid can be estimated based on structural engineering knowledge through the substitution model “grid”. Either way, the inserted typical idealized elements allow the application of common engineering expert knowledge for the assessment and preliminary design of load bearing structures. For this further processing, required parameters of single positions in ALoD 2a are the element type, boundary conditions, the lengths, the height and the load. Based on the given specifications in ALoD 0, the useful load is derived from the usage category and the foundation of the footings is evaluated from the soil condition. The continuing load transfer of the bearing structure is premised on a specified path that follows from slabs to vertical elements and from top to bottom. If the floor plan is provided by the architect, the development level of the model is raised from ALoD 0 to ALoD 1. Essential included parameters are the number and heights of floors, the arrangement of vertical building elements, slab and wall thicknesses, column cross-sections and openings. Thereby, considerable options are different floor and room compilations that might be suggested and mainly differ in the partial heights and lengths of the model or in the building construction type regarding wall and column arrangements. With the included geometrical information, the structural positions are identifiable through the positioning method raising the development level from ALoD 1 to ALoD 2a.

Otherwise, an estimation of the construction grid is realizable by using appropriate structural engineering knowledge that is essential content of the substitution model “grid”. The performed determination of a grid system and the related arrangement of vertical elements increases the model development status from ALoD 0 to ALoD 2a. For this purpose, suggestions for the specification of floors and slab kinds are necessary to enable the knowledge driven detection of structurally optimized segmentations of the total height and lengths. The buckling length of compression members highly influences the design of the vertical elements. Thus, floor configurations are proposed that are based on the division of the total height by common floor heights. Thereby, options are integrated for many small and few tall floors (see figure 2). Through the kind of slab, more specifically through the support types, suitable partial lengths are determined that are based on maximal slab position lengths featuring high possibility values for common slab thicknesses in consideration of the useful load. In the process, the resulting slab positions as well as the placement of wall and column positions for continuous and point supports are identified. For the consequential horizontal partitioning, further options are introduced for different slab bearing kinds and slab thicknesses (see figure 3). The resulting recommendation of construction grid systems involves the combination of options for floors and slab types (see figure 4). Analogously to the optimal slab position lengths and with respect to the load transfer, similar structural knowledge is utilized for the determination of wall thicknesses, column cross sections and footing dimensions to complement the building model for ALoD 2a. Thereby, different material or profile types are considerable through integration of options for various element styles.

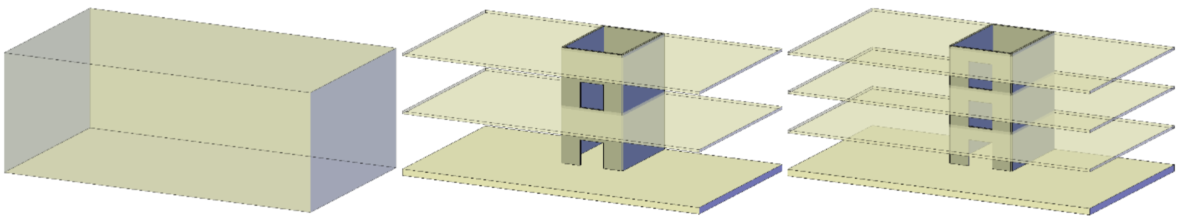


Figure 2: Blackbox in ALoD 0 and exemplary floor suggestions with anticipated stiffening core

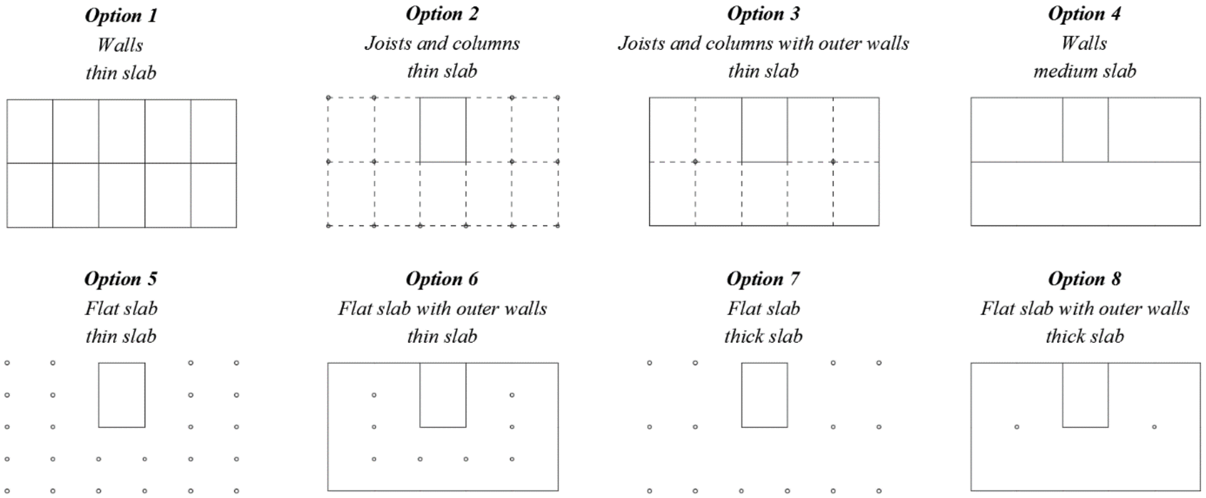
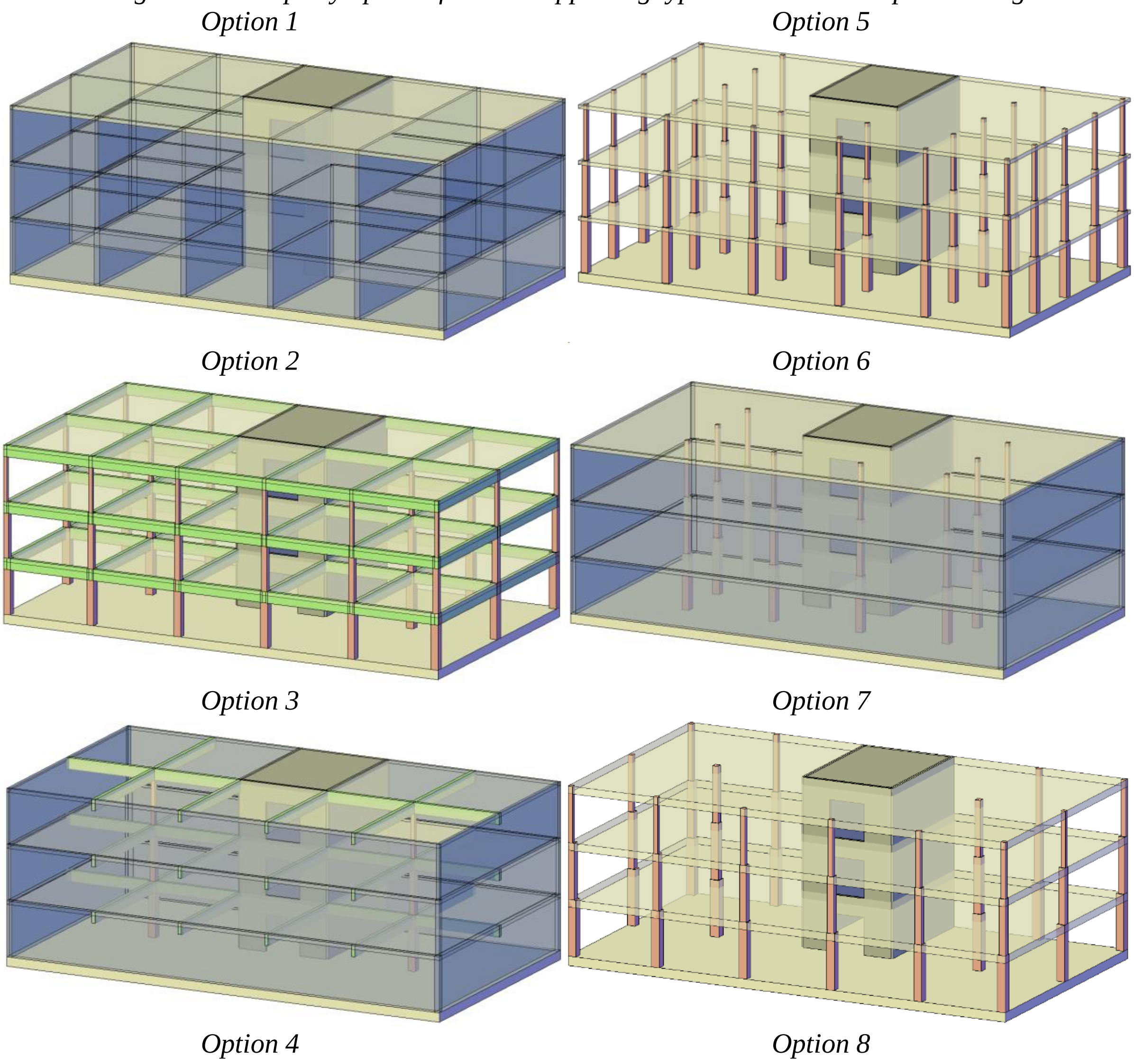


Figure 3: Exemplary options for slab supporting types and horizontal partitioning



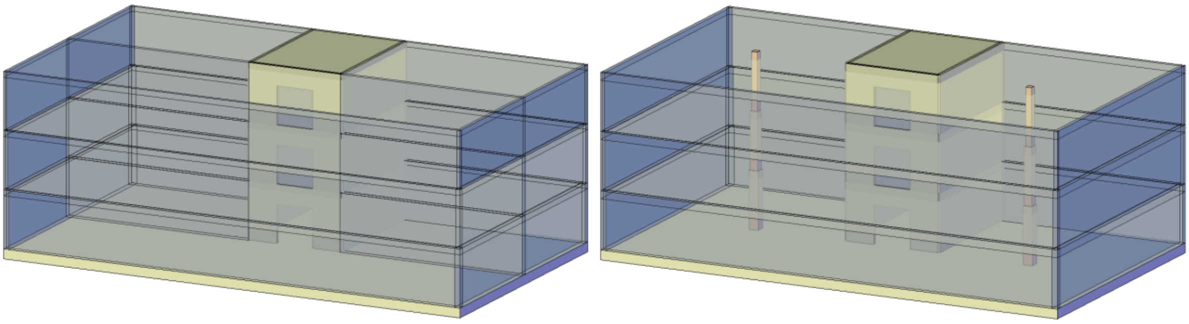


Figure 4: Exemplary models in ALoD 2a following the suggested grid options with three floors

The resulting structural element related information in ALoD 2a allows the possibility assessment through the substitution model “possibility” that raises the development level of the model to ALoD 2b. For each position in each option, the evaluated possibility values indicate the structural rating that is based on engineering expert knowledge for different construction types. Calculations of the values are based on the specific structural component and its parameters for geometry and load in ALoD 2a. If the construction grid is suggested through the substitution model “grid”, high possibility values are expected, as these indicate highly applicable elements. The delivery of a floor plan by the architect might trigger fuzzy requests, as low structural ratings are expectable more easily due to the different design perspective. This change management concept is performed for model modification requests in ALoD 2a and is based on assessments through the possibility values in ALoD 2b (Steiner and Schnellenbach-Held, 2018; Schnellenbach-Held and Steiner, 2019). With the structural evaluation of the building model, the selection of an appropriate option regarding the possible construction types is encouraged and the relating design decisions are supported.

For the selected designs, the final parameters for the preliminary design are determined by the substitution model “pre-design” that raises the development level from ALoD 2b to ALoD 3. The performed assessment of the exact material, the reinforcement and potential complementary information in ALoD 3 is based on the generated engineering expert knowledge. For the consideration of supplementary parameters, the ALoD-system features according concepts of adaptive detailing, so that further structures like precasted elements, assembly parts or other construction types are specifiable. With the geometry and load of the elements in ALoD 2a, the estimations are executed for the specific structural positions featuring the highest possibility values in ALoD 2b. In the process, options are considerable for different material strengths leading to varying reinforcement masses. By integration of the final model parameters, the building model assessment for the preliminary design is finished from the structural engineering perspective.

3.2 Alternating design progression

Through adaptivity of the developed ALoD system, the utilization of the same engineering expert knowledge and substitution models for structural assessments is enabled for alternating detailing approaches and related design progressions (Steiner and Schnellenbach-Held, 2018). For this purpose, the simultaneous presence of structural elements in different ALoDs as well as a related substitution model splitting are allowed. In the process, the consideration of partial parameter pre-specifications and of the varying information flow is needed. The application of the developed detailing and assessment system for structural engineering on an alternating design procedure is demonstrated by means of a meta model approach that includes another development level specification with building design levels (BDLs) (Abualdenien and Borrmann, 2019). The principle of adaptive detailing is outlined per ALoD to BDL adjustments (see table 2) and according separations of the inference systems. Due to the adaptation induced increase of the development resolution that especially arises from segmentations of the substitution model “grid”, more exemplary starting points for fuzzy requests are presentable. Through the adaptivity of the developed ALoD concept, the structural engineering perspective is integrated in alternating design progressions, allowing an improvement of interdisciplinary design procedures in early planning phases.

Table 2: Assignment of ALoDs to the BDL system

BDL	Basic representation	ALoD	Allocated information
1	*Building footprint on site surface*	*0*	*Shape and total lengths*
2	*Exterior surfaces*	*0*	*Total height*
3	*Exterior solids* *Slab thicknesses adapted from BDL 4* *Interior centerlines*	*1* *2a* *Partial 2b* *1* *Partial 2a*	*Geometry exterior elements* *Exterior elements* *Material type exterior elements* *Suggested slab thicknesses* *Interior elements without geometry*
4	*Exterior openings* *Interior solids*	*1* *1* *2a* *Partial 2b*	*Exterior openings* *Geometry interior elements* *Interior elements* *Material type interior elements*
5	*Interior openings* *Added structural design parameters* *Exterior layering*	*1* *3* *-*	*Interior openings* *Structural design parameters*

Based on an architectural perspective primary in the context of energy calculation demands, the BDL concept is a development level basis for an interdisciplinary building design process (Abualdenien et al, 2019). For the building model development in early stages, the BDL system provides five basic design levels (Abualdenien and Borrmann, 2019) that depend on geometrical specifications separated for exterior and interior components. The building footprint on the site surface in BDL 1 and the exterior building surfaces in BDL 2 are assignable to the blackbox in ALoD 0 including the global and environmental parameters. As before, the construction grid can be provided by other planning participants or estimated through structural engineering knowledge.

In contrast to the structural design process, the following BDL 3 (see figure 5) contains surfaces and centerlines for interior elements (partial ALoD 2a) in combination with solids (ALoD 2a) and material groups (partial ALoD 2b) for exterior components. Next to the specification by the architect followed by the positioning method, the principle layout of the slab positions and the according arrangement of vertical elements are determinable through the parts of the substitution model “grid” that are relevant for slab divisions. In consideration of the slab thickness suggested for BDL 4 (ALoD 1), the estimated slab partial lengths (ALoD 2a) are used to introduce approximate centerlines of vertical elements (partial ALoD 2a). This enables the determination of the load transfer that is necessary for the design evaluation of vertical structural elements. Subsequently, the layout of exterior components (ALoD 1, 2a) that especially are the roof slab and exterior walls, is determined through the related parts of the substitution model “grid”. Suitable material groups for the exterior elements are evaluated based on the possibility values (partial ALoD 2b) calculated by the substitution model “possibility” for the associated construction types. In the grid suggestion process, options are introducible for slab support types and slab heights as well as the layout and material groups – like masonry or aerated concrete for walls – of the exterior elements. The placement of a column is an example for potential fuzzy requests in the resulting BDL 3.

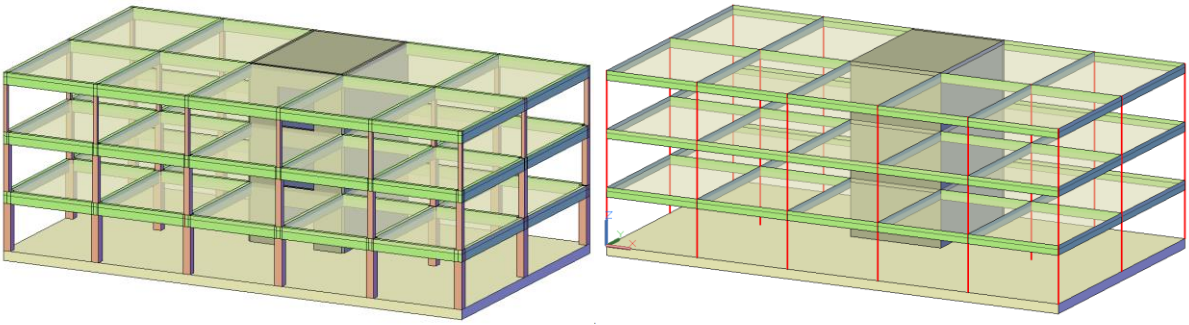


Figure 5: Comparison of ALoD 2a (left) and BDL 3 (right)

In BDL 4, parameters for exterior openings (ALoD 1) as well as solids (ALoD 1, 2a) and material groups (partial ALoD 2b) for interior structures are added to the building model. As openings to the outside that are inserted especially for doors and windows, may influence the wall layout, the possibility value might be reevaluated for exterior structures, if an earlier specification is missing. Analogously to the exterior components, the layout of interior elements is determined through the related parts of the substitution model "grid" combined with the possibility values for different construction types that are depending on material groups and calculated by the substitution model "possibility". In the process, options are presentable for the layout and material groups of the interior elements. Possible fuzzy requests in BDL 4 are, for instance, the adjustment of a beam height or the change of a column cross section. The final BDL 5 contains interior openings (ALoD 1), the layering of exterior components and ventilation information as well as the complemented structural design parameters (ALoD 3). Included are the exact material class, the reinforcement amount and possible construction related information. Like in the basic scenario, adaptive detailing concepts allow the consideration of further construction types. The determination of the structural information is realized by the substitution model "pre-design" for the exterior and the interior elements. Thereby, options are providable for different material strengths and fuzzy requests can exemplarily address the modification of openings in beams. By supplementation of the final parameters, the building model is developed to BDL 5 and the structural engineering assessment of the preliminary design is finished.

4. Conclusions

Interdisciplinarity is a significant factor for a successful planning in the building design process. Additionally, the supporting structure highly influences the applicability and efficiency of a building design. For these reasons, an integration of the structural engineering perspective in early planning phases is realized through the developed intelligent substitution models for preliminary structural assessments and design. They provide a decision support for the building design process based on structural engineering expert knowledge. For this purpose, fuzzy knowledge bases are formalized and generated that depend on identified development levels for structural design. Using a Fuzzy Logic approach, inference systems are developed for the expert knowledge to form the intelligent substitution models. Applicable structural engineering knowledge is generated through parameter studies and optimization tasks as well as complementary mapping processes. For demonstration of the enhanced building design process, two design scenarios for a simple fictional building are illustrated that involve the decision-making assistance. According to the developed ALoD-system, the first scenario follows the common progression for structural design. A different design procedure is based on an advanced architectural perspective that reveals an alternative development level system. Through adaptive detailing concepts that are integrated in the ALoD-system, the application of the developed intelligent substitution models is allowed for the differing design process.

Based on the evaluated design parameters, further model ratings from other planning disciplines are allowed. These may involve financial calculations or embedded and operational energy estimations for life cycle energy analyses (Abualdenien et al, 2019). As the integrated options represent an uncertainty of parameters in lower development levels, related quantification methods are enabled. For example, value ranges for grey energy or financial demands are determinable through backpropagation of option induced structural parameter variations. Additionally, requests for modification of the completed model take place that are characteristic for the current design process. As such changes usually provoke high efforts for impact evaluations and remodeling, a suitable change management is enabled by a methodology for structural assessments. The concept is based on the extension of the applied substitution models and the included engineering expert knowledge (Steiner and Schnellenbach-Held, 2018; Schnellenbach-Held and Steiner, 2019). The resulting decision support allows an optimization of the design process through enhancements of the continuity and the integrity.

Acknowledgements

This project is supported by the German Research Foundation (DFG) in the context of the research unit 2363 “Evaluation of building design variants in early phases using adaptive levels of development”. We are grateful to the DFG for its support.

References

Abualdenien, J., Borrmann, A. (2019). A meta-model approach for formal specification and consistent management of multi-LOD building models. Advanced Engineering Informatics 40, pp. 135-153, https://doi.org/10.1016/j.aei.2019.04.003.

Abualdenien, J., Borrmann, A., Exner, H., König, M., Zahedi, A., Petzold, F., Singh, M.M., Geyer, P., Harter, H., Schneider-Marin, P., Lang, W., Steiner, D., Schnellenbach-Held, M. (2019). Consistent management and evaluation of building models in early design stages. Journal of Information Technology in Construction, accepted paper.

El-Diraby, T. and Krijen, T. and Papagelis, M. (2017). BIM-based collaborative design and socio-technical analysis of green buildings. Automation in Construction 82, pp. 59-74.

Geyer, P., Singh, M.M., Singaravel, S. (2018). Component-Based Machine Learning for Energy Performance Prediction by MultiLOD Models in the Early Phases of Building Design. In: Advanced Computing Strategies for Engineering, pp. 516–534, https://doi.org/10.1007/978-3-319-91635-4_27.

Harter, H., Schneider-Marin, P., Lang, W. (2018). The Energy Grey Zone – Uncertainty in Embedded Energy and Greenhouse Gas Emissions Assessment of Buildings in Early Design Phases. In: Publications of the Sixth International Symposium on Life-Cycle Engineering, October 2018, Ghent.

Kim, J.I., Kim, J., Fischer, M., Orr, R. (2015). BIM-based decision-support method for master planning of sustainable large-scale developments. Automation in Construction 58, pp. 95-108.

Liu, H., Ong, Y.S., Cai, J. (2018). A survey of adaptive sampling for global metamodeling in support of simulation-based complex engineering design. Structural and Multi-disciplinary Optimization 57, pp. 393-416, https://doi.org/10.1007/s00158-017-1739-8.

Maier, J.F., Eckert, C.M., Clarkson, P.J. (2017). Model granularity in engineering design – concepts and frame-work. Design Science, Volume 3, Cambridge.

Mattern, H., König, M. (2018). BIM-based modeling and management of design options at early planning phases. Advanced Engineering Informatics, Vol. 38, pp. 316-329.

Oh, M., Lee, J., Wan Hong, S., Jeong, Y. (2015). Integrated system for BIM-based collaborative design. Automation in Construction 58, pp. 196-206, https://doi.org/10.1016/j.autcon.2015.07.015.

Schnellenbach-Held, M., Albert, A. (2003). Integrating knowledge based systems with Fuzzy logic to support the early stages of structural design (in German). Bauingenieur 11/2003, pp. 517-524.

Schnellenbach-Held, M., Hartmann, M. (2003). Using Knowledge Based Systems for Building Design in Computer Supported Cooperative Work. Darmstadt Concrete V18, Darmstadt.

Schnellenbach-Held, M., Hartmann, M., Pullmann, T. (2006): Knowledge Based Modeling in Network Cooperative Building Design using Elements of Fuzzy Logic. In: Proceedings of the XIth International Conference on Computing in Civil and Building Engineering, Montreal, http://www.irbnet.de/daten/iconda/CIB21117.pdf.

Schnellenbach-Held, M., Steiner, D. (2019): Change Management Concepts for Structural Design in Early Planning Phases. In: Proceedings of the 26th EG-ICE international workshop on intelligent computing in engineering, July 2019, Leuven, Belgium.

Steiner, D., Schnellenbach-Held, M. (2017). Realization of Adaptive Prestressing. In M. van Scheven & M.A., Keip & N. Karajan (eds.), Proceedings of the 7th GACM Colloquium on Computational Mechanics for Young Scientists from Academia and Industry, 11–13 October 2017, Stuttgart.

Steiner, D., Schnellenbach-Held, M. (2018). Intelligent Substitution Models for Structural Design in early BIM Stages. Publications of the Sixth International Symposium on Life-Cycle Engineering, October 2018, Ghent.

Steiner, D. (2018). Formulierung und Generierung von Expertenwissen zur Entwicklung intelligenter Ersatzmodelle für die Tragwerksplanung in frühen Entwurfsphasen (in German). Tagungsband 30. Forum Bauinformatik, 19–21 September 2018, Weimar.

Zahedi, A.; Petzold, F. (2018): Utilization of Simulation Tools in Early Design Phases Through Adaptive Detailing Strategies. In: 23rd CAADRIA 2018, vol. 2. Beijing, China, pp. 11–20.

Zhang, J., Li, H., Zhao, Y., Ren, G. (2018). An ontology-based approach supporting holistic structural design with the consideration of safety, environmental impact and cost. Advances in Engineering Software 115, pp. 26-39, https://doi.org/10.1016/j.advengsoft.2017.08.010.

Industry 4.0 in Construction: Practitioners' Perceptions

John Smallwood[1, *] and Chris Allen[1]
Nelson Mandela University
email: john.smallwood@mandela.ac.za

Abstract

Construction continues to experience challenges in terms of a range of issues, namely, following processes, certification, data gathering and recording, monitoring, availability of skilled labour, late payment of contractors, and a declining interest in pursuing careers in the industry. Then, challenges are experienced in terms of performance relative to the project parameters of cost, environment, health and safety, productivity, quality, and time.

Given the abovementioned, and the advent of Industry 4.0, an exploratory quantitative study was conducted to determine the challenges experienced, performance relative to the project parameters, and the potential of Industry 4.0 to contribute to resolving the former cited challenges.

The salient findings are: most project parameter-related phenomena, and construction resource-related phenomena are experienced frequently; there is a need for performance improvement relative to a range of resources and aspects; respondents rate themselves below average in terms of awareness of / exposure to most Industry 4.0 technologies, and Industry 4.0 technologies have the potential to reduce the occurrence of project parameter-related phenomena, and construction resource-related phenomena on projects. Conclusions include that that there is: a need for improvement in performance in construction; potential to improve; a need for the implementation of Industry 4.0, and a need for interventions to raise the level of awareness, and to integrate such technologies into built environment / construction education and training.

Recommendations include: employer associations, professional associations, and statutory councils should raise the level of awareness relative to the potential implementation of Industry 4.0 in construction; case studies should be documented and the findings shared; tertiary built environment education programmes should integrate Industry 4.0 into all possible modules, and continuing professional development (CPD) should address Industry 4.0.

Keywords: Construction, Industry 4.0, Performance

1. Introduction

Just a quarter of construction projects undertaken in the last three years were completed within 10% of their original deadlines (McKinsey in Autodesk & CIOB, 2019). Pryke, Managing Director, BAM Design, United Kingdom (UK) contends that "In some cases buildings are still being delivered 50% late and 50% over budget and there are still defects on site. Productivity has only increased by 1% in the last 20 years, so the industry is ripe for takeover." (Autodesk & CIOB, 2019). Drastically improving productivity and profitability remains one of construction's biggest challenges, which two factors are inextricably linked. For example, if the workforce is 10% less efficient than expected, profits are currently reduced by a minimum of 5% (The Construction Professional in Autodesk & CIOB, 2019). Furthermore, average UK construction project margins reduced to just 1% in 2017 (EY in Autodesk & CIOB, 2019).

Within the context of South Africa, the Construction Industry Development Board (cidb) (2016) highlighted a range of performance issues: clients were neutral or dissatisfied with the performance of contractors on 18% of the projects surveyed; clients were neutral or dissatisfied with the construction schedule performance of contractors on 26% of the projects; approximately 13% of the projects surveyed had levels of defects which are regarded as inappropriate; there was a noticeable increase in the levels of defects over the period 2012 to 2015; contractors were neutral or dissatisfied with the performance of clients on 18% of the projects surveyed; contractors were neutral or dissatisfied with the quality of tender documents and specifications obtained from clients on approximately 17% of the projects surveyed; contractors were neutral or dissatisfied with the management of variation orders on 24% of the projects surveyed; 60% of payments to contractors were delayed for longer than 30 days after invoicing; the recommendations of the tender committee were overruled in the award of approximately 9% of public sector projects, and H&S on construction sites as well as transportation to the sites remains a concern.

The Council for Scientific and Industrial Research (CSIR) (2018) states that the rapid rise and convergence of emerging technologies is driving the Fourth Industrial Revolution (FIR), also known as Industry 4.0. FIR is a collective term for technologies and value chain organisation which draw together cyber-physical systems, the Internet of Things (IoT) and the Internet of Services (IoS), together with other emerging technologies such as cloud technology, big data, predictive analysis, artificial intelligence, augmented reality, agile and collaborative robots, and additive manufacturing.

Considering the numerous challenges experienced in construction, especially the delivery of projects, it is inevitable that the FIR is considered to overcome these. According to Autodesk & CIOB (2019), digital technologies are transforming every industry, and construction is no exception. Infinite computing, robotics, machine learning, drones, the IoT, augmented reality, gaming engines, and reality capture, to name just a few, are innovating the design, build, and operation of buildings and infrastructure.

Furthermore, Schwab (2018) states that the world is volatile, uncertain, complex, and ambiguous, and therefore, for organisations to function in this fast-changing market they need to develop and incorporate smart digital ways to maintain their competitive advantage. The FIR, a combination of cyber physical systems, is driven by the increasing availability and interaction of a new set of extraordinary technologies, building on three previous technological revolutions. Much more than linking computers and creating higher levels of automation, the signature of the Third Industrial Revolution, it is more about how we learn from what we are doing by collecting state-of-the-art information on our methods, systems and processes and then using that through human or artificial intelligence to do things smarter.

Considering the numerous challenges experienced in construction, especially the delivery of projects, it is inevitable that the FIR is considered in terms of potential to overcome these. Furthermore, recent studies have highlighted that 26% of construction workers say they are frustrated by the lack of tools they need to do their jobs better (Autodesk & CIOB, 2019).

Industry 4.0 is only possible because of digitalisation, thus the approach to planning, decision making, organising, and operating in this age will in many ways be different from the current approach due to the greater amounts of information and learning systems available to assist. More autonomous and individual decisions are going to be made, which requires live and up-to-date information from various sources. This will not just be decision making at a management level but will encapsulate the principles enshrined in the ‘Toyota’ way, whereby individuals on the ‘production line’ can stop the process based on information available to them (Liker, 2004). This will see a skill shift with new formal, and informal competencies needed by these individuals, including enhanced communication skills. Manyika & Bughin (2018) contend that approximately half of current work activities (not jobs) are technically automatable.

Given the continuing poor performance in South African construction, and the cited benefits of implementing Industry 4.0 technologies, an exploratory study was conducted to determine the:

- Frequency that project parameter-related phenomena are experienced on projects;
- Frequency that eighteen-construction resource-related phenomena are experienced on projects;
- Extent of the need for performance improvement on projects;
- Respondents’ self-rating of their awareness of / exposure to ten Industry 4.0 technologies;
- Potential of Industry 4.0 technologies to reduce the occurrence of seven project parameter-related phenomena, and
- Potential of Industry 4.0 technologies to reduce the occurrence of eighteen construction resource-related phenomena.

2. Review of the Literature

2.1 The Fourth Industrial Revolution

Schwab (2018) states that the publication of The Fourth Industrial Revolution in January 2016 established the need to take collective responsibility "for a future where innovation and technology are centred on humanity and the need to serve the public interest." However, Schwab (2018) stresses the importance of developing a mindset that considers system-level effects, the impact on individuals, which remains future oriented and is aligned with common values across diverse stakeholder groups.

Furthermore, Schwab (2018) advocates that the following four principles should be kept in mind when considering how technologies can create impact: systems not technologies; empowering, not determining; by design, not by default, and values as a feature, not a bug. Cousins (2018) echoes a similar sentiment and states if staff are not onboard with the journey, it's possible that 'Big Brother syndrome' could result in distrust towards management, and create an additional source of workplace stress and low morale.

2.2 Data

Data is a powerful means of driving improvements across the global construction industry, but the built environment has not yet developed the capability to use data in a genuinely meaningful way (van Rooyen, 2015). Unmanageable volumes and complexity of 'big data' have driven the need for machine learning, which is difficult for humans to interpret using traditional analytical methods. The Health & Safety Executive (HSE) (2017) states that artificial intelligence (AI) is "the science of making machines smart", and is a field that is advancing at an exponential rate. Machine learning in turn, is a tool for constructing AI systems, involving extraction of knowledge and 'learning' from data.

Within the context of construction and the management of projects, worker health and safety (H&S) is an area which still needs much improvement. Ideally, 'big data' should enable people to determine what is transpiring, and how to intervene to improve a system such as an H&S management system. Much of the recent excitement with respect to AI has been the result of advances in the field known as deep learning, a set of techniques to implement machine learning based on artificial neural networks (Manyika & Bughin, 2018).

Then, the 'Internet of Things' (IoT) is one of the major up-and-coming new technologies that will play a role in reshaping work, which can most simply be described as "a technological development where everyday machines, devices and appliances are connected and able to send and receive data over the Internet." (HSE, 2017)

2.3 Benefits of Industry 4.0

McKinsey in Autodesk & CIOB (2019) reports that moving to a manufacturing-style production system could boost productivity in the construction sector by up to 10 times. Kranz (2017) in turn cites the payback relative to IoT as reduced labour, lower costs, increased productivity, improved quality, and enhanced decision making. Reduced labour due to IoT performing a task that a person would have had to do. Lower costs due to devices connecting and communicating to automate a process. Increased productivity due to such automation. Improved quality due to intelligent devices connecting and communicating through the IoT thus reducing errors and rework. Enhanced decision making, intelligent devices connecting and communicating through the IoT, especially if analytics or predictive analytics are included into the equation.

Recent advances in access technologies such as unmanned aerial vehicles (UAVs) or drones and Remotely Operated Vehicles (ROVs) coupled with imaging technology, have enabled increasing replacement of the human element in terms of visual inspection. This is beneficial in terms of avoidance of high-risk manned interventions such as in confined spaces, working at height, or in hazardous environments (HSE, 2019a). Cousins (2018) cites the real-time surveillance of job sites courtesy of

drones, and adds that they are increasingly being deployed to oversee H&S systems over large work areas.
According to the HSE (2019b), there is growing evidence that wearable devices can significantly benefit H&S in the workplace through positioning and sensor technologies. To this end, the priority areas for a pending research project are monitoring occupational personal exposure to hazardous substances and physical hazards on construction sites, and musculoskeletal disorders (MSDs) in workers identified at greater risk. Cousins (2018) in turn highlights that wearable devices can detect fatigue risk, high heart rates, and stress.
From a macro perspective, the findings of research conducted by the World Economic Forum (WEF) predicts that 10 years of full-scale digitalisation of the construction industry will lead to huge annual global cost savings. Savings in the design, engineering and construction phases in the non-residential construction sector are expected to increase from $0.7 trillion to $1.2 trillion, and in the operations phase, from $0.3 trillion to $0.5 trillion (WEF in Autodesk & CIOB, 2019).

3. Research

3.1 Research Method and Sample Stratum

The exploratory study entailed a self-administered questionnaire survey delivered via e-mail. The sample strata included alumni (graduates) of the Department of Construction Management, Nelson Mandela University, Construction H&S Agents, and Master Builders Association (MBA) Kwazulu-Natal H&S competition award winners. The questionnaire consisted of fourteen questions – thirteen closed ended, and one open-ended. Seven of the close ended questions were Likert scale type questions, and six were demographics related. 46 Responses were received, which equates to a response rate of 16.1%. The analysis of the data entailed the computation of frequencies, and a measure of central tendency in the form of a mean score (MS), to enable the interpretation of percentage responses to Likert point scale type questions, and the ranking of variables.

3.2 Results and Discussion

Table 1 indicates the frequency at which seven project parameter-related phenomena are experienced on projects in terms of percentage responses to a scale of never to constantly, and a MS ranging between 1.00 and 5.00. It is notable that only 5 / 7 (71.4%) of the MSs are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the phenomena to be experienced on projects. It is notable that no phenomena are experienced between often to constantly / constantly (MSs > 4.20 ≤ 5.00). 5 / 7 (71.4%) of the MSs are > 3.40 ≤ 4.20, which indicates the frequency is between sometimes to often / often – delays, poor productivity, late completion, quality non-conformances, and costs exceed value, which are inter-related in that they impact upon each other. Damage to the environment has a MS > 2.60 ≤ 3.40 – between rarely to sometimes / sometimes. The MS of accidents is marginally below the lower limit of the upper MS range. The pervasiveness of these phenomena are frequently referred to in the literature (cidb, 2016; Autodesk & CIOB, 2019).

Table 1: Frequency at which project parameter-related phenomena are experienced on projects.

Phenomenon	Response (%)						MS	Rank
	Unsure	Never	Rarely	Some-times	Often	Constantly		
Delays	0.0	0.0	7.0	16.3	46.5	30.2	4.00	1
Poor productivity	0.0	2.3	9.3	27.9	37.2	23.3	3.70	2
Late completion	2.3	2.3	14.0	25.6	32.6	23.3	3.62	3
Quality non-conformances	0.0	0.0	9.3	39.5	34.9	16.3	3.58	4

Costs exceed value	2.3	0.0	9.3	41.9	34.9	11.6	3.50	5
Damage to the environment	0.0	4.7	41.9	34.9	9.3	9.3	2.77	6
Accidents	0.0	0.0	62.8	23.3	7.0	7.0	2.58	7

Table 2 indicates the frequency at which eighteen construction resource-related phenomena are experienced on projects in terms of percentage responses to a scale of never to constantly, and a MS ranging between 1.00 and 5.00. It is notable that 13 / 18 (72.2%) of the MSs are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the phenomena to be experienced on projects. However, the MSs of four phenomena are on the cut-point, namely 3.00. It is notable that no phenomena are experienced between often to constantly / constantly (MSs > 4.20 ≤ 5.00). 6 / 18 (33.3%) of the MSs are > 3.40 ≤ 4.20, which indicates the frequency is between sometimes to often / often – late information, a shortage of workers with the necessary skills, information anomalies / ambiguities, rework occurs, inadequate coordination of subcontractors, and similar or alike errors are repeated. It is notable that 2 / 6 (33.3%) are information-related. The MS (3.40) of data / statistics is / are not available, ranked seventh, which is information-related, is on the lower point of the upper MS range. The remaining twelve (66.7%) phenomena have MSs > 2.60 ≤ 3.40 – between rarely to sometimes / sometimes. It is notable that three (25.0%) phenomena are information-related, ‘difficulty monitoring the process and activities of construction’ included. 5 / 12 (41.6%) are in the upper half of the range, namely > 3.10 ≤ 3.40 - data / statistics is / are not available, underpricing, management information is not available, materials are not available when required, and difficulty monitoring the process and activities of construction. The MSs of a further two are 3.10, namely fatigue among workers, and materials are lost / stolen. These are followed by unauthorised people fulfill functions, workers are regularly absent, poor plant and equipment utilisation, materials are damaged, and sprains and strains among workers. Many of these are frequently referred to in the literature (HSE, 2017; 2016; Autodesk & CIOB, 2019; HSE, 2019a; HSE, 2019b).

Table 2: Frequency at which construction resource-related phenomena are experienced on projects.

Phenomenon	Response (%)						MS	Rank
	Unsure	Never	Rarely	Some-times	Often	Constantly		
Late information	0.0	0.0	4.7	20.9	46.5	27.9	3.98	1
A shortage of workers with the necessary skills	4.7	2.3	7.0	23.3	34.9	27.9	3.83	2
Information anomalies / ambiguities	4.7	2.3	4.7	30.2	41.9	16.3	3.68	3
Rework occurs	2.4	0.0	9.5	45.2	33.3	9.5	3.44	4
Inadequate coordination of subcontractors	0.0	0.0	20.9	27.9	32.6	18.6	3.49	5
Similar or alike errors are repeated	2.3	0.0	11.6	41.9	30.2	14.0	3.48	6
Data / Statistics is / are not available	7.0	2.3	18.6	20.9	41.9	9.3	3.40	7
Underpricing	7.0	2.3	11.6	37.2	32.6	9.3	3.38	8
Management information is not	7.1	0.0	19.0	31.0	33.3	9.5	3.36	9

available								
Materials are not available when required	7.0	0.0	23.3	39.5	20.9	9.3	3.18	10
Difficulty monitoring the process and activities of construction	4.7	2.3	25.6	27.9	37.2	2.3	3.12	11
Fatigue among workers	9.3	4.7	18.6	34.9	27.9	4.7	3.10	12
Materials are lost / stolen	2.3	2.3	18.6	51.2	18.6	7.0	3.10	13
Unauthorised people fulfill functions	9.3	11.6	18.6	30.2	18.6	11.6	3.00	14
Workers are regularly absent	7.0	2.3	30.2	32.6	20.9	7.0	3.00	15
Poor plant and equipment utilisation	7.0	4.7	23.3	39.5	18.6	7.0	3.00	16
Materials are damaged	4.7	2.3	18.6	53.5	18.6	2.3	3.00	17
Sprains and strains among workers	4.7	0.0	41.9	30.2	16.3	7.0	2.88	18

Table 3 indicates the extent of the need for performance improvement on projects in terms of percentage responses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00. It is notable that the MSs are all above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the need for improvements to be major as opposed to minor. It is notable that only 4 / 17 (23.5%) MSs are > 4.20 ≤ 5.00, which indicates the respondents perceive the need for improvement to be between near major to major / major - improved communication, workers with technical skills, integration of information (construction), and integration of information (design). One need is communication-related, and two are integration of communication-related. These needs, including workers with technical skills, can be responded to by Industry 4.0 technologies. Improved planning & control of activities on site, ranked fifth, has a MS of 4.19, which is marginally below the lower point of the upper MS range. The 12 (66.7%) needs ranked fifth to sixteenth have MSs > 3.40 ≤ 4.20, which indicates the respondents perceive the need to be between some improvement to a near major / major improvement. 8 / 12 (66.7%) of these needs fall in the upper half of the range, namely > 3.8 ≤ 4.20 - improved planning & control of activities on site, integration of information (procurement), link processes across the stages of projects, reduced occurrence of H&S incidents / accidents, digitalisation of information, workers with technology skills, deployment of technology, and improved security. These needs are varied, however, they can be responded to by Industry 4.0 technologies. The needs in the lower half of the range, namely improved materials management, modern plant and equipment, simulation of activities, and automation of activities on site, can be responded to by Industry 4.0 technologies. Workers with IT skills, has a MS marginally below the lower point of the upper MS range, and thus falls within the range > 2.60 ≤ 3.40, which indicates a near minor need to some need / some need. Yet again, the empirical findings reflect the findings of the literature in terms of the implied need for performance improvement (Autodesk & CIOB, 2019; cidb, 2016).

Table 3: Extent of the need for performance improvement on projects.

Need	Response (%)						MS	Rank
	Un-sure	Minor ……………………………Major						
		1	2	3	4	5		
Improved communication	0.0	0.0	2.3	4.7	44.2	48.8	4.40	1

Workers with technical skills	2.3	0.0	0.0	11.6	34.9	51.2	4.40	2
Integration of information (construction)	0.0	0.0	0.0	16.3	39.5	44.2	4.28	3
Integration of information (design)	0.0	0.0	0.0	18.6	41.9	39.5	4.21	4
Improved planning & control of activities on site	0.0	0.0	2.3	23.3	27.9	46.5	4.19	5
Integration of information (procurement)	0.0	2.3	2.3	16.3	37.2	41.9	4.14	6
Link processes across the stages of projects	2.3	0.0	0.0	23.3	41.9	32.6	4.10	7
Reduced occurrence of H&S incidents / accidents	0.0	2.3	9.3	14.0	27.9	46.5	4.07	8
Digitalisation of information	4.7	0.0	7.0	16.3	34.9	37.2	4.07	9
Workers with technology skills	4.7	2.3	2.3	20.9	39.5	30.2	3.98	10
Deployment of technology	2.3	0.0	4.7	27.9	37.2	27.9	3.90	11
Improved security	0.0	2.4	7.1	31.0	16.7	42.9	3.90	12
Improved materials management	0.0	2.3	7.0	25.6	41.9	23.3	3.77	13
Modern plant and equipment	0.0	0.0	7.0	39.5	27.9	25.6	3.72	14
Simulation of activities	9.3	2.3	9.3	27.9	25.6	25.6	3.69	15
Automation of activities on site	7.1	2.4	7.1	26.2	40.5	16.7	3.67	16
Workers with IT skills	4.7	7.0	11.6	32.6	25.6	18.6	3.39	17

Table 4 indicates the respondents' self-rating of their awareness of / exposure to ten Industry 4.0 technologies in terms of percentage responses to a scale of 1 (limited) to 5 (extensive), and a MS ranging between 1.00 and 5.00. It is notable that only 3 / 10 (30.0%) of the MSs are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to rate themselves as above average, as opposed to below average. It is notable that no technology is rated above average to extensive / extensive (MSs > 4.20 ≤ 5.00). Only 1 / 10 (10.0%) MSs is > 3.40 ≤ 4.20, which indicates a rating of average to above average / above average - Internet of Things. Only 2 / 10 (20.0%) MSs are > 2.60 ≤ 3.40, which indicates a rating of below average to average / average - digitalisation of information, and drones. The remaining 7 / 10 MSs are > 1.80 ≤ 2.60, which indicates a rating of limited to below average / below average. Virtual reality, and 3-D printing fall within the upper half of this MS range, whereas blockchain, augmented reality, artificial intelligence (AI) / machine learning, robotics / exoskeletons, and nanotechnology fall within the lower half.

Table 4: Respondents' self-rating of their awareness of / exposure to ten Industry 4.0 technologies.

Technology	**Response (%)**						**MS**	**Rank**
	Un-sure	**Limited ………………………..Extensive**						
		1	**2**	**3**	**4**	**5**		
Internet of Things	7.1	7.1	2.4	23.8	35.7	23.8	3.72	1
Digitalisation of information	0.0	16.7	11.9	16.7	33.3	21.4	3.31	2
Drones	0.0	18.6	9.3	30.2	27.9	14.0	3.09	3
Virtual Reality	0.0	32.6	16.3	25.6	14.0	11.6	2.56	4
3-D printing	2.3	39.5	20.9	14.0	16.3	7.0	2.29	5
Blockchain	11.6	32.6	27.9	18.6	4.7	4.7	2.11	6
Augmented Reality	7.0	48.8	11.6	14.0	14.0	4.7	2.08	7
Artificial Intelligence (AI) / Machine Learning	2.3	41.9	25.6	18.6	9.3	2.3	2.02	8
Robotics / Exoskeletons	2.3	48.8	18.6	20.9	4.7	4.7	1.95	9
Nanotechnology	4.8	47.6	23.8	16.7	2.4	4.8	1.88	10

Table 5 indicates the potential of Industry 4.0 technologies to reduce the occurrence of seven parameter-related phenomena in terms of percentage responses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00. It is notable that the MSs are all above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the potential to be above average.

It is notable that no MS is > 4.20 ≤ 5.00 – near major to major / major potential. All 7 MSs are > 3.40 ≤ 4.20, which indicates between potential to near major / near major potential. The top three ranked phenomena, namely late completion, quality non-conformances, and delays are clustered. Despite the respondents' generally low self-rating of their awareness of / exposure to ten Industry 4.0 technologies, they recognise the potential of Industry 4.0 technologies to reduce the occurrence of the parameter-related phenomena as per the literature (Autodesk & CIOB, 2019).

Table 5: Potential of Industry 4.0 technologies to reduce the occurrence of project parameter-related phenomena.

Phenomenon	**Response (%)**						**MS**	**Rank**
	Un-sure	**Minor ……………………………Major**						
		1	**2**	**3**	**4**	**5**		
Late completion	11.9	0.0	9.5	23.8	26.2	28.6	3.84	1
Quality non-conformances	11.6	0.0	7.0	23.3	37.2	20.9	3.82	2
Delays	11.6	2.3	7.0	16.3	41.9	20.9	3.82	3
Poor productivity	9.3	2.3	11.6	20.9	27.9	27.9	3.74	4
Costs exceed value	14.0	2.3	11.6	18.6	30.2	23.3	3.70	5
Damage to the environment	14.0	2.3	14.0	25.6	20.9	23.3	3.57	6
Accidents	11.9	2.4	14.3	23.8	28.6	19.0	3.54	7

Table 6 indicates the potential of Industry 4.0 technologies to reduce the occurrence of eighteen construction resource-related phenomena in terms of percentage responses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00. It is notable that except for one MS all the other MSs (94.4%) are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the potential to be above average. It is notable that no MS is > 4.20 ≤ 5.00 – near major to major / major potential. 12 / 18 (66.7%) MSs are > 3.40 ≤ 4.20, which indicates between potential to near major / near major potential. 6 / 12 (50.0%) of these phenomena fall in the upper half of the range, namely > 3.80 ≤ 4.20 - information anomalies / ambiguities, difficulty monitoring the process and activities of construction, similar or alike errors are repeated, management information is not available, data / statistics is / are not available, and rework occurs. The other six phenomena fall in the lower half of the range, namely late information, inadequate coordination of subcontractors, underpricing, poor plant and equipment utilization, unauthorised people fulfill functions, and materials are not available when required. The phenomena ranked thirteenth to seventeenth have MSs > 2.60 ≤ 3.40, which indicates between near minor to potential / potential, namely materials are damaged, sprains and strains among workers, materials are lost / stolen, fatigue among workers, and a shortage of workers with the necessary skills. The MS (2.59) of workers are regularly absent is marginally below the lower point of the upper MS range. However, the potential is nevertheless between minor to near minor / near minor. As is the case of the parameter-related phenomena, despite the respondents' generally low self-rating of their awareness of / exposure to ten Industry 4.0 technologies, they recognise the potential of Industry 4.0 technologies to reduce the occurrence of the resource-related phenomena as per the literature (Autodesk & CIOB, 2019).

Table 6: Potential of Industry 4.0 technologies to reduce the occurrence of construction resource-related phenomena.

Phenomenon	**Response (%)**						**MS**	**Rank**
	Un-sure	**Minor ……………………………Major**						
		1	**2**	**3**	**4**	**5**		
Information anomalies / ambiguities	7.0	2.3	4.7	11.6	37.2	37.2	4.10	1
Difficulty monitoring the process and activities of construction	4.7	2.3	2.3	18.6	39.5	32.6	4.02	2
Similar or alike errors are repeated	4.8	2.4	4.8	26.2	26.2	35.7	3.93	3

Management information is not available	7.0	4.7	4.7	23.3	25.6	34.9	3.88	4
Data / Statistics is / are not available	7.0	7.0	9.3	16.3	18.6	41.9	3.85	5
Rework occurs	7.0	2.3	2.3	32.6	25.6	30.2	3.85	6
Late information	4.7	4.7	4.7	27.9	27.9	30.2	3.78	7
Inadequate coordination of subcontractors	4.7	2.3	9.3	23.3	37.2	23.3	3.73	8
Underpricing	7.0	7.0	9.3	11.6	39.5	25.6	3.73	9
Poor plant and equipment utilisation	7.0	2.3	7.0	30.2	32.6	20.9	3.68	10
Unauthorised people fulfill functions	9.3	4.7	16.3	14.0	32.6	23.3	3.59	11
Materials are not available when required	9.5	7.1	11.9	16.7	31.0	23.8	3.58	12
Materials are damaged	9.3	7.0	16.3	34.9	18.6	14.0	3.18	13
Sprains and strains among workers	7.1	11.9	16.7	23.8	23.8	16.7	3.18	14
Materials are lost / stolen	9.3	18.6	11.6	18.6	20.9	20.9	3.15	15
Fatigue among workers	4.8	9.5	19.0	28.6	26.2	11.9	3.13	16
A shortage of workers with the necessary skills	11.9	14.3	14.3	23.8	21.4	14.3	3.08	17
Workers are regularly absent	7.1	26.2	23.8	19.0	9.5	14.3	2.59	18

4. Conclusions

Given the frequency that project parameter-related phenomena are experienced on projects by respondents, it can be concluded that the respondents' experience reflects the general research findings relative to project performance in South African construction, and that there is a need for improvement, potential to improve, and a need for the implementation of Industry 4.0.

Given the frequency that eighteen construction resource-related phenomena are experienced on projects by respondents, it can be concluded that the respondents' experience reflects the general research findings relative to project performance in South African construction, and that there is a need for improvement, potential to improve, and a need for the implementation of Industry 4.0. The frequency, and thus the need and potential are notable relative to information, however, also applicable to the other resources such as labour, materials, and plant.

Given the extent of the need for performance improvement on projects in terms of integration, linkages, mitigation of errors, automation, digitalisation, simulation, security, and technology, it can be concluded that the respondents' experience reflects the general research findings relative to project performance in South African construction, and that there is a need for the implementation of Industry 4.0.

Given the respondents' below average self-rating of their awareness of / exposure to ten Industry 4.0 technologies, it can be concluded that there is a need for interventions to raise the level of awareness, and to integrate such technologies into built environment / construction education and training. However, this should be expedited in a contextual manner.

Given the potential of Industry 4.0 technologies to reduce the occurrence of seven project parameter-related phenomena, and eighteen construction resource-related phenomena on projects, the need for the implementation of Industry 4.0 in construction is amplified.

Recommendations

Built environment-related tertiary education must include, or rather embed Industry 4.0 in their programmes.

Construction employer associations, and built environment associations and statutory councils must promote, and preferably provide Industry 4.0 continuing professional development (CPD), and evolve related guidelines and practice notes.

The Construction Industry Development Board (cidb) should evolve a position paper relative to Industry 4.0 in construction, and deliberate the development of a related industry standard.

Researchers should actively conduct and document Industry 4.0 case studies to record the benefits of implementing Industry 4.0 technologies.

References

Autodesk and Chartered Institute of Building (CIOB), 2019. *Discussion Paper Reimagining construction: The vision for digital transformation, and a roadmap for how to get there*. London: CIOB.

Construction Industry Development Board (cidb), 2016. The cidb Construction Industry Indicators:

Summary Results 2015. Pretoria: cidb.

The Council for Scientific and Industrial Research (CSIR) (2018). Industry 4.0 PLM Centre of Technology. Pretoria: CSIR.

Cousins, S., 2018. Workplace monitoring: Orwell's world of work. Health and Safety at Work, November 2018 [online]. Downloaded from: https://www.healthandsafetyatwork.com/feature/orwells-world-of-work [Accessed 1 May 2019]

Health & Safety Executive (HSE), 2017. Foresight Report 2016. Buxton, Derbyshire: HSE.

Health & Safety Executive (HSE), 2019a. Shared Research Project Remote Visual Inspection (RVI). London: HSE.

Health & Safety Executive (HSE), 2019b. Shared Research Project Wearables in the Workplace. London: HSE.

Kranz, M., 2017. Building the Internet of Things. Hoboken, New Jersey: John Wiley & Sons, Inc.

Liker, J., 2004. The Toyota Way. India: McGraw-Hill Education.

Manyika, J. & Bughin, J. 2018. The promise and challenge of the age of artificial intelligence. New York: McKinsey Global institute.

Schwab, K., 2018. Shaping the Future of the Fourth Industrial Revolution. London: Portfolio Penguin.

Van Rooyen, K. 2015. Beyond big data – a route map to data maturity. London: Turner & Townsend plc.

Experimentation to Support Real-Time Monitoring of Mobile Crane Operations

Congwen Kan[1*], Chimay J. Anumba[2], and John I. Messner[3]
[1]M. E. Rinker, Sr. School of Construction Management, University of Florida, Gainesville, FL, USA
[2]College of Design, Construction and Planning, University of Florida, Gainesville, FL, USA
[3]Department of Architectural Engineering, Pennsylvania State University, University Park, PA, USA
* email: congwen.kan@ufl.edu

Abstract

Monitoring mobile crane motion in real-time is the first step to identifying and mitigating potential mobile crane-related hazards on construction sites. Although standard motions of a mobile crane, such as hoisting, luffing, and slewing of the load can be captured by existing techniques, a reliable approach to accurately position the load and monitor the base motion remains elusive. This study seeks to address this problem by exploring an approach to monitor mobile crane motion comprehensively and consistently in real-time. Two types of sensors are adopted in this approach: 1) inertial measurement unit (IMU) for monitoring the crane load position and sway, and 2) proximity sensing system (iBeacon technology) for monitoring the base motion as well as locating the mobile crane with respect to items on the construction site. This proposed approach was tested in a controlled lab setting. Scenarios were developed to test 1) if the sensory data can be processed and converted to reconstruct the mobile crane motion in a virtual model, 2) if the crane motion can be continuously and accurately modelled in real-time, 3) if potential hazards associated with mobile crane operations can be well detected, and 4) if this approach effectively presents the crane operator with crane motion information and warns them of potential hazards. By enabling real-time monitoring of crane motions and pro-actively warning of the potential hazards, this approach will advance safety practices in mobile crane operations.

Keywords: Real-time monitoring, IMU, iBeacon, Mobile crane

1. Introduction

The construction industry has long been criticized for its poor safety records. Cranes as one of the central components applied widely in many construction projects, are associated with a large fraction of construction fatalities. According to Neitzel et al. (2001), crane-related fatalities account for one third of the total fatalities in the construction industry. As the two mostly used types of crane in the construction industry, tower cranes and mobile cranes have very distinct uses. While tower cranes sit at a fixed location and operate within a given workspace, mobile cranes have more mobility and flexibility in performing the lifting tasks. According to a study conducted by Kan et al. (2018a), from 2006 to 2016, mobile crane-related fatalities totaled 325 in the US construction industry, accounting for 56% of the crane-related fatalities.

Accidents caused by the operation of cranes are always associated with severe consequences such as occupational injuries and fatalities. Research was conducted to isolate the causes of crane-related accidents, and it was claimed that lack of visibility for crane operators was the principal contributing factor (Hinze and Teizer, 2011). While performing the lifting tasks, crane operators do not receive adequate information concerning the object being lifted and the surrounding conditions. As for mobile crane, the visibility is even more limited since the crane cabin in which the operator sits is attached to the crane base on the ground. The operator's visibility can be easily blocked by obstructions on site or the building under construction. Thus, monitoring mobile crane operations in real-time and providing visual feedback to the crane operator is the first step to identifying and mitigating potential mobile crane-related hazards on construction sites. Although standard motions of a mobile crane, such as hoisting, luffing, and slewing of the load can be captured by existing techniques, a reliable approach to accurately position the load and consistently monitor the base motion remains elusive.

With the aim of advancing mobile crane safety practices, this paper presents a multi-sensor-based approach to monitoring mobile crane motions comprehensively and consistently in real-time. Two types of sensors are adopted: 1) inertial measurement unit (IMU) for monitoring the crane load position and sway, and 2) proximity sensing system (iBeacon technology) for monitoring the base motion as well as locating the mobile crane with respect to items on the construction site. This proposed approach was tested in a controlled lab setting. Scenarios were developed to test 1) if the sensory data can be processed and converted to reconstruct the mobile crane motion in a virtual model, 2) if the crane motion can be continuously and accurately modelled in real-time, 3) if potential hazards associated with mobile crane operations can be well detected, and 4) if this approach effectively presents the crane operator with crane motion information and warns them of potential hazards. The remaining part of this paper is structured as follows: first, existing methods for monitoring crane operations are discussed. Then, the proposed sensor-based method being developed for real-time mobile crane operations monitoring is described. This method was tested in a controlled lab setting and the preliminary results are presented. The concluding part of this paper highlights the limitations of this approach and future steps in implementing the sensing system.

2. Related Work

The first known crane monitoring system was developed by Bernold et al. in 1999 and patented in 2002. This monitoring system incorporated a variety of sensors mounted to a crane and an on-board control unit. The control unit stored data collected by the sensors and processes these data to identify unsafe crane conditions, defined as alarm events. Each alarm event was time stamped, and data resulting from the time prior to the alarm event until the conclusion of the event were logged and stored in the control unit. The stored data can be accessed later on and analysis can be conducted against the operations which trigger the alarm event (Bernold et al., 2002). This crane monitoring system was not on a real-time basis, but it brought the crane safety issue to the forefront and represented a good start towards realizing real-time monitoring of crane operations.

Recent studies related to this issue are mostly sensor-based. Lee et al. (2009) introduced a laser-based real-time tower crane lifting path tracking system. In their study, the laser was installed at the tip of the boom, and a reflection board was installed on the hook block. The position information was acquired through the laser beam reflected from the reflection board. However, it was pointed out that this approach was more reliable in measuring the vertical distance between the lifted load and the boom. It failed to position the load three-dimensionally due to the load sway.

Zhang and Hammad (2012) employed a real-time location system (RTLS) using ultra-wideband (UWB) to collect location data of the objects on site and calculate crane poses. In this system, UWB tags were deployed on several spots of the crane boom, and all mobile objects such as workers were equipped with UWB readers when entering the monitored area. It was stated that by using the near real-time updated information, crane pose was estimated, and potential collisions could be detected and avoided. However, there were several practical problems. For instance, UWB works in certain frequency range. The emission of the signal experienced significant loss when falling out of range. In addition, the strength of the signal fluctuates easily due to the existence of interference sources on site. In view of this, the UWB-based approach failed to track the crane poses and load position continuously and stably.

Another major research stream is camera-based. For instance, Lee et al. (2006) deployed a video camera system on tower crane to improve the crane operator's visibility while lifting. A wireless video camera was mounted on the trolley of the tower crane to continuously capture the top view of the lifted load. Videos were transmitted through the wireless communication module to the central computer module and displayed on a monitor installed in the crane cabin. The system was tested in a project using multiple tower cranes and the system was only deployed on one of the tower cranes. It was claimed that considerable improvement could be seen in lifting productivity through the comparative experiment. Communication between the operator and the signal person was also more efficient using the camera system. The camera system provided the crane operator an alternative perspective for the lifting job, however, the vertical view of the lifted load did not provide the operator with enough sense of proximity to the surroundings. The estimation on the position of the load was still subject to the operator's own judgment. In addition, the video camera system was sensitive to the environmental conditions (such as light), and it was ineffective in high-rise building due to the increased distance between the camera and the lifted load.

In these previous attempts, the monitoring of load sway was not well addressed. The monitoring systems that have been developed failed to provide the operator with enough sense of proximity to the surroundings. In addition, existing research on real-time operation monitoring are mostly on tower cranes. Very limited number of researches has taken account of the mobility of the cranes on site. In this regard, an approach to accurately and consistently monitor the mobile crane operations is needed to address the persisting problems that previous research failed to address.

3. Methodology

In this section, the two types of sensors adopted in this study, IMU and iBeacon technology are introduced. The following sub-sections highlight the sensor's specific use cases, the mobile device used for visualization, and the communication network used for data transmission.

3.1 Mobile crane motion data capture -- IMU

An IMU is an electronic device assembled with a combination of accelerometers, gyroscopes, and sometimes magnetometers. It measures and reports a body's gravitational forces, angular orientation, and sometimes the magnetic field surrounding the body (Dissanayake et al., 2001). The IMU sensor estimates orientation by combining the data it gets from three types of sensors: 1) a gyroscope which measures angular motion, 2) an accelerometer which measures the acceleration due to gravity, as well as any other accelerations that occur, and 3) a magnetometer which measures magnetic direction. The readings from the compass and accelerometer are used together to form the absolute component of orientation, which is used to correct any short term changes the gyroscope makes (Dissanayake et al., 2001).

Generally, an IMU sensor has one accelerometer and one gyroscope for each of the three axes. When rigidly mounted to a point, the IMU sensor measures the linear and angular acceleration and automatically calculates the orientation of the object attached to this point (Zhang et al., 2005). With the ability to track position changes and report inertial measurements, IMU was chosen to capture the position of the crane load and monitor the load sway. Two IMUs were proposed for installation at the tip of the boom and on the hook block, as shown in Figure 1. The illustration here is a crawler lattice boom crane, but the uses are not limited this specific crane type.

Given the measured angular orientation of each axis, the estimated position of the boom and the hook can be calculated by converting the Euler angle measurements to Cartesian coordinates in the local coordinate system (Raab et al., 1979). The axes of the original frame are denoted as x, y, z and the axes of the rotated frame as X, Y, Z. φ represents a rotation around the z axis, θ represents a rotation around the y axis, ψ represents a rotation around the x axis, as shown in Figure 2.

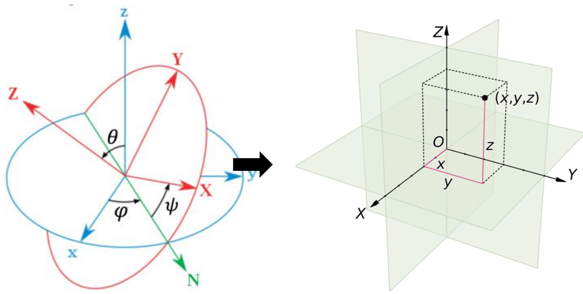


Figure 1: IMUs' Location on a Mobile Crane (left)
Figure 2: Transforming the Angular Measurements to Absolute Positions (right)

The orientation measurements of one single load can be decomposed into three axes. The individual rotation matrices for each axe are given in Equation (1), (2) and (3) (Raab et al., 1979).

$$M_z(\varphi) = \begin{bmatrix} cos\varphi & -sin\varphi & 0 \\ sin\varphi & cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \ldots(1) \qquad M_z(\theta) = \begin{bmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{bmatrix} \ldots(2) \qquad M_z(\psi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\psi & -sin\psi \\ 0 & sin\psi & cos\psi \end{bmatrix} \ldots(3)$$

Therefore, a single rotation matrix, as shown in Equation (4), can be formed by multiplying the rotation matrices for the three axes. The converted IMU data are used to reconstruct the location of the boom and hook/lifted load. These are then transmitted to a mobile device for the crane operator to visualize the crane motion.

$$M\ (\varphi,\theta,\psi) = M_z(\varphi) \times M_y(\theta) \times M_x(\psi) = \begin{bmatrix} cos\varphi \times cos\theta & cos\varphi \times sin\theta \times sin\psi - sin\varphi \times cos\psi & cos\varphi \times sin\theta \times cos\psi + sin\varphi \times sin\psi \\ sin\varphi \times cos\theta & sin\varphi \times sin\theta \times sin\psi + cos\varphi \times cos\psi & sin\varphi \times sin\theta \times cos\psi - cos\varphi \times sin\psi \\ -sin\theta & sin\theta \times cos\psi & cos\theta \times cos\psi \end{bmatrix} \quad (4)$$

3.2 Mobile crane motion data capture – iBeacon

As one of the primary crane motions, the proximal location of the crane is measured by the iBeacon. The iBeacon proximity sensing system is based on Bluetooth wireless sensing technology. The units adopted in this study are Estimote location beacons. The maximum communication range is up to 150 meters, and its frequency ranges from 2400 MHz to 2483.5 MHz. The output power is adjustable: from -20 dBm to +4 dBm in 4 dB steps, to take account for both short-range communication and long-range communication. The proximity sensing system incorporates Bluetooth signal transmitter (iBeacon) and crane operator's receiver (mobile device mounted in the crane cabin). This iBeacon-based proximity sensing system is leveraged to locate the mobile crane and to create a hazard detection area so that alerts will be sent to the crane operator when potential collisions are detected.

In the case of creating a hazard detection area, a three-level warning system is created, as shown in Table 1. The iBeacons which constantly transmit Bluetooth signal are to be placed on mobile objects on site, such as workers. The mobile device, possibly a tablet, which is able to scan for the Bluetooth signal is installed in the crane cabin. In this way, the distance between any objects on site and the mobile crane are monitored and warning messages displayed on the tablet once potential collision hazards are detected.

Table 1: Collision Warning System

Collision Probability	Safety Threshold	Warning Message Triggered	Denoting Colour
Elevated	15 feet	Danger ahead, need to decelerate	Yellow
High	10 feet	Moderate danger ahead, decelerate immediately	Orange
Severe	5 feet	Critical situation, stop immediately	Red

The proximal location of the mobile crane is measured through the use of triangulation with three iBeacons (Liu et al., 2007). It is represented as (X, Y) in the coordinate system developed within Unity 3D. iBeacons a, b, and c are iBeacon sub-classes with pre-set X and Y values, where (X_a, Y_a) represents the location of beacon a, (X_b, Y_b) represents the location of beacon b, and (X_c, Y_c) represents the location of beacon c. The proximal location of a mobile crane, (X, Y) can be calculated using Equation (5) and (6) shown as follows:

$$Y = ((T \times (X_b - X_c)) - (S \times (X_b - X_a))) / (((Y_a - Y_b) \times (X_b - X_c)) - ((Y_c - Y_b) \times (X_b - X_a))) \quad (5)$$

$$X = ((Y \times (Y_a - Y_b)) - T) / (X_b - X_a) \quad (6)$$

where $S = (X_c^2 - X_b^2 + Y_c^2 - Y_b^2 + D_b^2 - D_c^2) / 2$

$T = (X_a^2 - X_b^2 + Y_a^2 - Y_b^2 + D_b^2 - D_a^2) / 2$

$D = 10\ (txPower - RSSI) / 20$

* RSSI stands for Received Signal Strength Indicator, and txPower stands for calibrated transmitter power.

* The txPower is denoted as the known measured signal strength in RSSI at 1 meter away. Both txPower and RSSI are provided by the iBeacon manufacturer.

An example of using triangulation to determine the location is shown in Figure 3. The three iBeacons are placed on the perimeter of a rectangle. The distances between these three are known so their locations in the coordinate system developed in Unity 3D are known as well. If one is manually set to (0, 0) for the ease of calculation, the locations of the other two can be denoted as (20, 20) and (40, 0). The mobile device, which is the tablet mounted in the crane cabin, is able to receive the Bluetooth signal that the three iBeacons transmitt, so that the RSSI and txPower for the three are known. In this regard, the location of a mobile crane (X, Y) can be calculated using Equation (5) and (6).

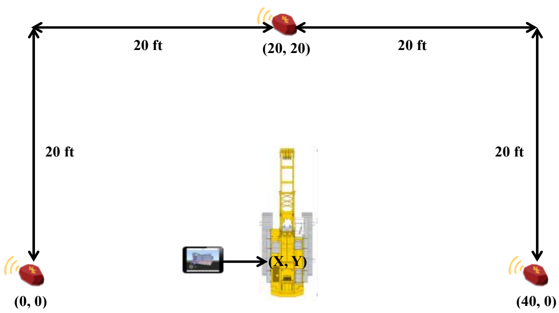


Figure 3: Triangulation Example

3.3 Mobile devices for visualization

Mobile devices adopted in this study are portable computing devices which have a screen for displaying information, such as tablet PC and Bluetooth enabled smart phones. The mobile device is installed in the crane cabin. It is intended to provide the operator with real-time mobile crane operational conditions as well as the surrounding site conditions, and any supplementary information such as warning messages triggered. Messages shown on the mobile device and auditory warnings are used in this study to indicate hazardous situations.

Figure 4 shows an example of visualizing the crane operational conditions. This virtual platform was developed in Unity 3D. More details concerning how the platform was built and what control algorithms were embedded within the platform can be obtained from Kan et al. (2018b).

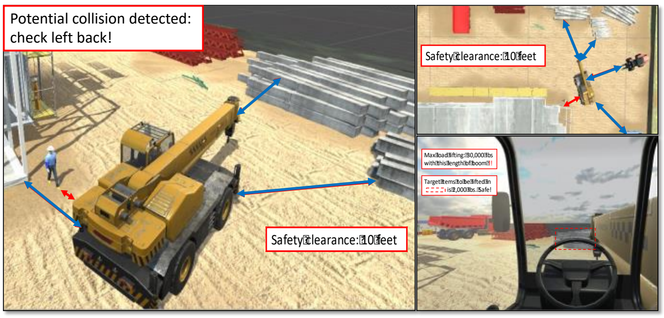


Figure 4: Example Crane Operation Visualization Shown on a Mobile Device (Kan et al., 2018b)

3.4 Communication network

The communication network enables communication and coordination between the virtual platform and the physical mobile crane on site by enabling sensory data exchange. The communication network adopted in this study includes the Internet and wireless fidelity (Wi-Fi) for IMU data transmission and Bluetooth for iBeacon data transmission. The sensory data are transferred through the communication network to the virtual platform on the central server, which is a local computer. With the mobile device connected wirelessly to the computer, the operational conditions of the mobile crane can be visualized by the crane operator.

4. Lab Test & Results

The following sub-sections present the tests performed on IMU and iBeacon respectively. Results are discussed at the end of each sub-section.

4.1 IMU

The objectives of the experiment include: 1) to test if the IMUs are capable of tracking the location of the boom and monitoring the load sway and 2) if the sensory data can be processed and converted to re-construct the mobile crane motion in the virtual platform.

To simulate the condition of crane load sway, firstly a tripod was equally spaced and firmly fixed on the ground to establish a stable levelled point. A round load with an IMU vertically attached was hung using a steel chain and securely mounted through the levelled point, as shown in Figures 5 (a) and (b). The IMU used in this study is a 2.4GHz wireless sensor from YostLabs. A direct sequence spread spectrum (DSSS) communication interface in conjunction with a rechargeable lithium-polymer battery are embedded into a single end-use-ready unit. The on-board gyroscope, accelerometer, and magnetometer in conjunction with the processing algorithms are capable of reporting the location relative to an absolute reference in real-time. A communication dongle unit is needed in order to transmit the data to the central computer, as shown in Figure 6. The data received by the computer are constantly written to a txt. file for further analysis, as shown in the bottom of the computer screen in Figure 6.

Figure 5: Load Sway Simulation: (a) tripod setup and (b) IMU sensor (left)

Figure 6: Dongle Unit Connected to a Laptop (right)

In order to test the capability of IMU in monitoring the crane load sway, a scenario was designed. The load hosting the IMU sensor was lifted 0.3 meters off its original resting position with the steel chain fully stretched and was released with a lateral force. Consequently, the load started to sway annularly. A total of 973 measurements were captured by the IMU in around 60 seconds, and then the load was stopped manually. The measurements recorded in the txt. file were exported into Excel for analysis. The conversion algorithm introduced in the previous section was applied and load sway trajectory was simulated. The results shown in Figure 7 (a), (b) and (c) are for XY, YZ and XZ plane respectively, with the dots denoting the exact measurements and lines mapping out the trajectory. It should be noted that the unit is in meters.

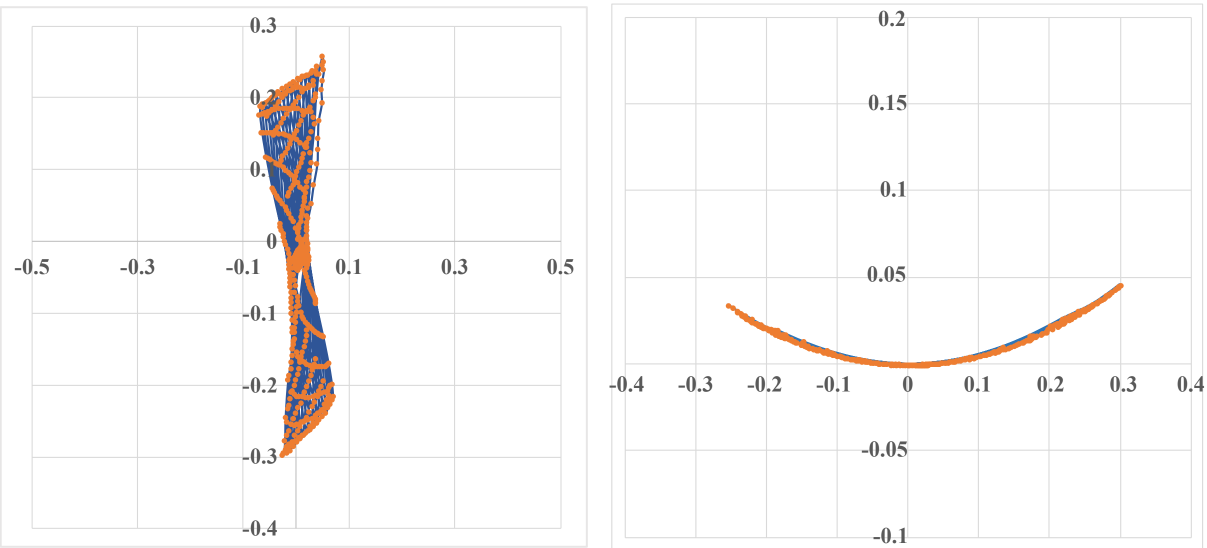
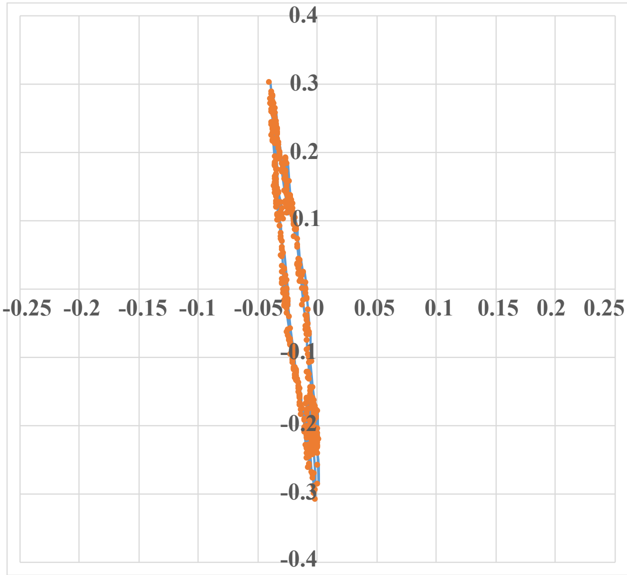


Figure 7: (a) Sway trajectory in XY plane *(b) Sway trajectory in YZ plane*



(c) Sway trajectory in XZ plane

As indicated by the results, the load sway is an evenly-displaced oval shape, which matches what was observed during the experiment. In this regard, the IMU is capable of tracking the load sway. In addition, the successful re-construction of the load position also indicates that the algorithm for transforming angular measurements to absolute positions works as expected. Thus, the proposed use of IMUs for monitoring and visualizing the positions of the crane boom and load can be further carried out on site for full-scale validation.

It should be noted that drift was observed during the lab experiments. The drift of the IMU plays a major role in causing some degree of precision loss in the velocity, attitude and position data provided by the unit. Moreover, the drift and precision rates tend to change each time the IMU unit is turned on. In this regard, the drift effect must be adequately considered in order for the IMU unit to capture the load and boom positions accurately in the long term. In future experiments, algorithms adapted from historical inertial data would be used to conduct IMU drift correction upon static positions. In addition, Kalman filter is also proposed to be used to estimate the drifts of the unit and to reduce the accumulated error of the IMU.

4.2 iBeacon

The iBeacon-based proximity sensing system was tested with two scenarios to establish 1) if the potential collision hazards could be well detected and 2) if this approach presents the crane operator with proximal crane location.

In order to test the first use case scenario with iBeacon, creating a hazard detection area around the mobile crane, a model with a sole function built-in, ‘reporting the distances between the iBeacons and the mobile device’ was developed in Unity 3D. For ease of reading, the distances between the iBeacons and the mobile device were set to be displayed in a red rectangle in the center, and any warning messages triggered were displayed in the top left corner of the screen, as shown in Figures 8 (a) and (b). In Figure 8 (a), the mobile device was placed in close proximity to the iBeacon, and the distance read in the red rectangle are on a 0.00 (meter) scale. When moving the device away from the iBeacon, the distance read increased, as shown in Figure 8 (b).

In order to further test the function of triggering warning messages, the three-level collision warning system stated in the previous section was added to the model. The function was tested by people with the iBeacons approaching the mobile device from different angles. Figure 9 shows an example of a ‘serve’ condition. One iBeacon were identified to be within 5 feet (1.43 feet) as shown on the top right corner of Figure 9, and a warning message was triggered and was displayed in red.

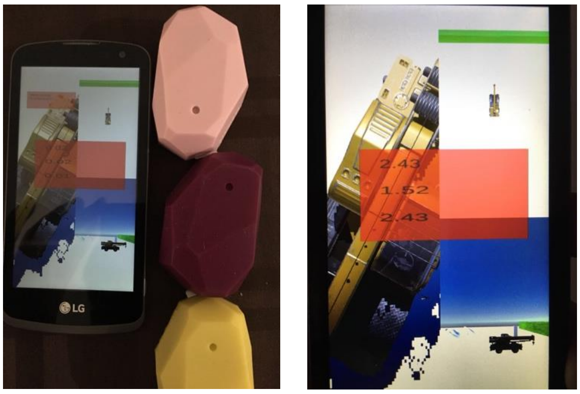


Figure 8: The Distance Read on the Mobile Device:(a) iBeacons in close proximity and (b) increased distance between the mobile device and iBeacons (left)
Figure 9: Example Visualization of a Warning Message (right)

The second scenario with iBeacon was to determine the proximal location of the crane using the triangulation method. The method was tested in a 16 x 16 ft room. As shown in Figure 10, the three iBeacons were placed on three sides of the room, while the mobile device was placed in between these three. The mobile device was carried and moved in the room, and the location changes for the device were tracked on the central computer.

The triangulation algorithm has been embedded into the virtual platform, with the locations of the three iBeacons manually set to (0, 0), (8 ft, 8 ft) and (16 ft, 0) in this specific case. The three numbers displayed in the top left corner of Figure 11 indicate the distances between the mobile device and the three iBeacons, and the location of the mobile device is represented as the intersection of the three circles. This simple 2D illustration was created in Unity 3D as a separate testing scene apart from the scene with the crane model, and it is only used to visualize the location changes more clearly.

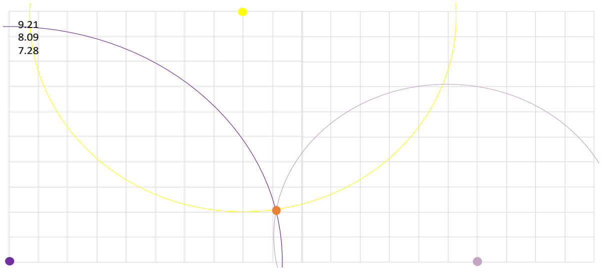


Figure 10: Lab Settings *Figure 11: Mobile Crane Location Determination*

The two test scenarios gave out very sensitive results, which comes from the nature of RSSI. In the first scenario, the distances between the iBeacons and the mobile device are calculated once a RSSI is returned by the iBeacon. The RSSI readings are not very stable and highly depend on the transmission power setting as well as environmental factors. The Bluetooth signals can suffer interference, be diffracted or absorbed. In this sense, the distance calculated is not very accurate. In the second scenario, the location of the mobile device is calculated based on the distances between the three iBeacons and the mobile device. The (X, Y) was set to be calculated once five RSSI readings are received, and the median of the five is used. It takes around two seconds for one calculation to be performed based on the transmission power setting. The problem within this setting is that, the time it takes for the system to receive 5 updates from each of the three iBeacons varies, so the calculations could not reflect the location changes on X and Y at the same time. In addition, the three distances calculated are not accurate on their own, so error accumulation occurs.

Issues that might also account for the error in the results were observed during the tests, and are summarized as follows:

- RSSI goes down if any obstruction is placed between the iBeacon and the mobile device. The reason for this is that, iBeacon signal is a series of radio waves that bounce off obstructions such as walls, ceilings, objects…etc. If a radio wave bounces off an obstruction, and then reaches the mobile device, its strength will be smaller than a radio wave that goes straight from an iBeacon to the mobile device.

- Placing the mobile device at different positions, such as carrying in the pocket, also affects the RSSI.
- The model of the mobile device affects the RSSI (Different antenna affecting the signal propagation… etc.).

Based on the lab test results, the iBeacon technology is not recommended to be used to locate the mobile crane. And in the case of creating a collision hazard detection area, additional algorithm can be added to remove the outliers in the data. If the positioning error can be reduced to an acceptable limit, iBeacons can be used to determine the relative distances between the crane and the mobile objects on site.

5. Conclusions

This paper has presented an approach to monitor mobile crane operations comprehensively and consistently in real-time. Two types of sensors were adopted for various purposes: 1) IMU for monitoring the crane boom position and load sway, and 2) iBeacon for determining the location of the mobile crane as well as locating the crane with respect to other mobile objects on the construction site. Tests were conducted for the two types of sensors respectively in a controlled lab setting. Scenarios were developed to test 1) if the sensory data can be processed and converted to re-construct the mobile crane motion in the virtual model, 2) if the crane motion can be continuously and accurately modelled in real-time, 3) if potential collision hazards can be well detected, and 4) if this approach effectively presents the crane motion information and any warning messages triggered. The results indicate that the IMU is capable of monitoring and visualizing the positions of the crane boom and load. Experiments should be carried out on construction sites for full-scale validation. As for iBeacon, it can be used to create a collision hazard detection area around the crane. Algorithms should be added to the existing model to filter out the irregular data, thus providing a more reliable result. iBeacon is not recommended to be used to locate the mobile crane unless better mechanisms/algorithms are found.

The next step of this research will focus on the validation of IMU and finding an alternative approach for locating the mobile crane. Field tests on a real construction site are planned to demonstrate the practical functionality of the system.

Acknowledgements

This paper is based upon work supported by the National Science Foundation under grant no. 1729209.

References

Bernold, L. E., Lorenc, S. J., Elliott, S. D., Cobb, M. S., & Green, A. R. (2002). Crane monitoring and data retrieval systems and method. United States Patent No. US6496766B1. Retrieved from https://patents.google.com/patent/US6496766B1/en

Dissanayake, G., Sukkarieh, S., Nebot, E., & Durrant-Whyte, H. (2001). The aiding of a low-cost strapdown inertial measurement unit using vehicle model constraints for land vehicle applications. IEEE Transactions on Robotics and Automation, 17(5), 731–747. https://doi.org/10.1109/70.964672

Hinze, J. W., & Teizer, J. (2011). Visibility-related fatalities related to construction equipment. Safety Science, 49(5), 709–718. https://doi.org/10.1016/j.ssci.2011.01.007

Kan, C., Zhang, P., Fang, Y., Anumba, C.J., & Messner, J.I. (2018a). A Taxonomic Analysis of Mobile Crane Fatalities for CPS-based Simulation. 17th International Conference on Computing in Civil and Building Engineering (Mela, K., Pajunen, S., & Raasakka, V. (eds.)), Tampere, Finland, June 5-7.

Kan, C., Anumba, C. J., & Messner, J. I. (2018b). A Framework for CPS-based Real-time Mobile Crane Operations. 35th CIB W78 2018 Conference: IT in Design, Construction, and Management (Mutis, I., & Hartmann, T. (eds.)). Advances in Informatics and Computing in Civil and Construction Engineering, Chicago, IL, USA, October 1-3. https://doi.org/10.1007/978-3-030-00220-6_78

Lee, U.-K., Kang, K.-I., Kim, G.-H., & Cho, H.-H. (2006). Improving Tower Crane Productivity Using Wireless Technology. Comp.-Aided Civil and Infrastruct. Engineering, 21, 594–604. https://doi.org/10.1111/j.1467-8667.2006.00459.x

Lee, G., Kim, H.-H., Lee, C.-J., Ham, S.-I., Yun, S.-H., Cho, H., … Kim, K. (2009). A laser-technology-based lifting-path tracking system for a robotic tower crane. Automation in Construction, 18(7), 865–874. https://doi.org/10.1016/j.autcon.2009.03.011

Liu, H., Darabi, H., Banerjee, P., & Liu, J. (2007). Survey of Wireless Indoor Positioning Techniques and Systems. IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), 37(6), 1067–1080. https://doi.org/10.1109/TSMCC.2007.905750

Neitzel, R. L., Seixas, N. S., & Ren, K. K. (2001). A review of crane safety in the construction industry. Applied Occupational and Environmental Hygiene, 16(12), 1106–1117.

Raab, F. H., Blood, E. B., Steiner, T. O., & Jones, H. R. (1979). Magnetic Position and Orientation Tracking System. IEEE Transactions on Aerospace and Electronic Systems, AES-15(5), 709–718. https://doi.org/10.1109/TAES.1979.308860

Zhang, P., Gu, J., Milios, E. E., & Huynh, P. (2005). Navigation with IMU/GPS/digital compass with unscented Kalman filter. IEEE International Conference Mechatronics and Automation, 2005, 3, 1497-1502 Vol. 3. https://doi.org/10.1109/ICMA.2005.1626777

Zhang, C., & Hammad, A. (2012). Multiagent Approach for Real-Time Collision Avoidance and Path Replanning for Cranes. Journal of Computing in Civil Engineering, 26(6), 782–794. http://doi.org/10.1061/(ASCE)CP.1943-5487.0000181

Digitalisation of Construction Organisations in South Africa: A Dynamic Capability Theory Approach

Douglas Aghimien[1,] *, Clinton Aigbavboa[1], Ayodeji Oke[1]
[1]SARChi in Sustainable Construction Management & Leadership in the Built Environment, Faculty of Engineering and the Built Environment, University of Johannesburg, South Africa
*email: aghimiendouglas@yahoo.com

Abstract

Digitalisation is a key driver of the Fourth Industrial Revolution and the digital transformation of construction organisations, for better service delivery, has become a popular clamour among academics and construction professionals alike. However, both the digital world and the construction industry are dynamic in nature. Therefore, a construction organisation that will attain sustained competitive advantage in this ever-changing environment through the digitalisation of its operations, must carefully consider its dynamic capabilities. Based on this knowledge, this study set out to create a direction through which construction organisations in developing countries like South Africa can increase their dynamic capability to attain a competitive advantage through the digitalisation. In achieving this, the dynamic capabilities needed by construction organisations were assessed through a review of the Dynamic Capability Theory. Findings revealed that construction organisations need to grow their dynamic capabilities in the area of sensing of opportunities and threats within their environment, seizing of sensed opportunities, and reconfiguring of their organisational resources to conform with the ever-changing environment. Some notable factors needed towards attaining these feats are investing in research and development, careful selection of digital technologies, tapping into suppliers and complementor's digital innovations, understand changing clients' needs, selecting the right decision-making procedure, controlling challenging assets, and many more. The findings of the study can serve as a starting point for the awakening of construction organisations that seek to gain a competitive advantage over their competitors through digitalisation of their services.

Keywords: Competitive Advantage, Digitalisation, Digital transformation, Digital technologies, Dynamic Capability Theory

1. Introduction

All over the world, the construction industry is dynamic, and its activities are not static. This uncertain nature of the industry can be attributed to the clients' growing demand, the complexity of construction projects, advancement in technology and the introduction of digital innovations (Navon, 2005; Oke and Ogunsemi, 2011). Clients' taste and demand are not static, and construction participants are saddled with the responsibility of meeting these demands through every available method. This situation has placed stiff competition among construction organisations, who take up the responsibility of delivering construction projects in return for a particular financial reward. For these organisations to survive this obviously competitive environment, strategic planning and adoption of innovative ideas are important (Aghimien *et al*., 2018a). One such approach is the adoption of digital technologies (DTs) which are key instruments geared towards attaining digitalisation.

It has been stated that digitalisation is the application of DTs in the operations of an organisation (Kalavendi, 2017). Ochs and Riemann (2018) described it as the use of DTs in everyday life, through digitising anything that is capable of being digitised. According to Crampton (2017), digitalisation is the use of DTs to transform the business model of an organisation, while at the same time providing new revenue streams and value-producing opportunities. Based on the aforementioned descriptions, in the context of this study, the term digitalisation is conceptualised as the "innovative use of DTs in the delivery of tangible and intangible services within a construction organisation with a view towards gaining a competitive advantage over other competitors, and providing better service delivery".

It is interesting to note that while the construction industry is ever-changing, the digital world is also dynamic in nature (Solis, 2016). Therefore, a construction organisation that will attain sustained competitive advantage in this uncertain environment through digitalisation, must carefully consider its dynamic capabilities. These dynamic capabilities are believed to be responsible for the adjustment in the usual routines of an organisation (Winter, 2003). It has been seen as an organisations ability to utilise its internal and external resources to address rapidly changing environment (Tecee *et al*., 1997), organisational routines used in achieving new resources that brings about market change (Eisenhardt and Martin, 2000), as well as a learned pattern of collective activities used by an organisation to generate and modify its operations in order to attain improved effectiveness (Zollo and Winter, 2002). Khin and Ho (2018) have noted that the ability to implement the DTs in the operations of an organisation is the first step towards attaining competitive advantage. Similarly, studies have observed that if DTs can be implemented in a manner that promotes the main strategic and operational objectives of an organisation, then significant benefits can be derived in the area of organisational performance (Chen *et al*., 2014; McLaughlin, 2017) and significant competitive advantage can be attained (Teece, 2007). It is based on this knowledge that this study set out to create a roadmap with which construction organisations in developing countries like South Africa can increase their dynamic capabilities to attain competitive advantage through the digitalisation of their operations. This was done through the review of the extant literature on dynamic capability theory.

2. Digitalisation of the construction industry

There have been four industrial revolutions that have altered mankind's way of existence. First is the human's transitioning from being a hunter-gatherer society to agrarian society, and from then on to becoming an industrialised society. From the industrial transformation came the advancement in information, and this saw human society becoming more information-oriented with the use of information technologies (Ozlu, 2017). Currently, the fourth phase of the industrial revolution known as the Fourth Industrial Revolution (4IR) is upon us. The 4IR is essentially the application of diverse technologies in an organisation or industry's activities. It is believed that digitalisation is a key driver of the 4IR as most of the technologies and processes that characterise the revolution is digital in nature (Bienhaus and Haddud, 2017). Crampton (2017) defined it as "the use of DTs to change the business model, provide new revenue streams and value-producing opportunities". Dimick (2014) viewed DTs from three facets and these are software, information technology equipment (computers and related hardware), and communications equipment. Example of these DTs include the building information modeling (BIM) which according to Ashcraft (2007) "utilises cutting-edge digital technology to establish a computable representation of all the physical and functional characteristics of a facility and its related project life-cycle information, and it is intended to be a repository of information for the facility owner/operator to use and maintain throughout the life-cycle of a facility". Ibem and Laryea (2014) described BIM as one of the most popular technologies that have gained significant recognition within the construction industry in recent time. There is also augmented reality, which is an innovation that gives an augmented view of objects or designs using specific gadgets (Celaschi, 2017); Internet of Things (IoT) which implies an overall system of network which are linked to each other and uniformly addressed objects by means of standard conventions (Vaidya *et al.*, 2018); and big data analytics which is viewed as the most vital technology in relation to the large collection, preparation, and investigation of unorganised and organised information with savvy algorithms (Petrillo *et al*., 2018). There is also the use of autonomous robots in performing autonomous production (Bahrin *et al.*, 2016), cloud computing wherein scalable IT-related capabilities are provided as a service over the Internet to multiple external customers (Kumar and Ravali, 2012; Noor *et al*., 2013), 3D printing which is the process of creating a physical object from a 3D digital model in a layer by layer process (Lim *et al.*, 2012), and many other technologies which are gradually gaining recognition within the construction industry.

De Andrade Régio *et al.* (2016) have noted that the implementation of these DTs is still in the early stages, and only a few have been adopted by the construction industry. Similarly, other studies have revealed that despite the immense benefits proposed by the application of DTs, its adoption within the construction industry is considerable low (Argawal *et al*., 2016; Castagnino *et al.*, 2016; Osunsanmi *et al*., 2018). De Andrade Régio *et al.* (2016) opined that the espousal of DTs and the application of its concept will provide construction organisations with a competitive advantage over their counterparts. According to Petrillo *et al*. (2018), this adoption will further help improve efficiency and productivity within the workplace and maximise flexibility. However, Bienhaus and Haddud (2017) noted that although digitalisation is important and propose significant benefits, the approaches towards achieving digital transformation in organisations differ in terms of how organisations picture its inherent opportunities and handle its challenges.

3. Dynamic Capability Theory

The Dynamic Capability Theory (DCT) is an extension of the Resource-based view (RBV) which has been described as a theoretical framework which influences the organisations understanding of how competitive advantage can be achieved and sustained (Eisenhardt and Martin, 2000; Teece *et al*., 1997). According to Zhou and Li (2010), RBV suggests that competitive advantage within an organisation can only be derived through an organisation's valuable, rare, inimitable, and non-substitutable resources. This view has however come under various criticism, most significant of which is the submission of Teece *et al.* (1997) that the foundation of the RBV is not strong enough to support the attainment of sustainable competitive advantage. This submission was based on the fact that though the RBV take into consideration some mechanisms that can lead to the attainment of competitive advantage within an organisation, how these mechanisms go about sustaining this competitive advantage is totally omitted. This criticism led to the development of the DCT by David Teece and Gary Pisano in 1994. According to Teece *et al*. (1997), the current business environment is not static as it has a continuously shifting landscape. An organisation that will attain a sustainable competitive advantage over its competitors and survives in this rapidly changing environment must have a dynamic capability. It is through this dynamic capability that its manager can effectively utilise both the internal and external competencies of the organisation that will tackle the changes within the business environment.

Teece and Pisano (1994) have earlier clarified that the term "dynamic" is "the capacity to renew competences so as to achieve congruence with the changing business environment". "Capabilities" are referred to as "the key role of strategic management inappropriately adapting, integrating and reconfiguring, internal and external organisational skills, resources, and functional competencies to match the requirements of a changing environment". Thus, by definition, Teece *et al.* (1997) defined dynamic capabilities as "the firm's ability to integrate, build and reconfigure internal and external competencies to address rapidly changing environments". However, due to the broad recognition of the DCT, other prolific definitions of the term have evolved (Wollersheima and Heimeriks, 2016). A significant one is the definition of Eisenhardt and Martin (2000) which stated that dynamic capability is "the organisational and strategic routines by which firms achieve new resource configurations as markets emerge, collide, split, evolve, and die". Similarly, Zollo and Winter (2002) defined it as "a learned and stable pattern of collective activity through which the organisation systematically generates and modifies its operating routines in pursuit of improved effectiveness." Drawing from these three major definitions it is clear that the dynamic capabilities of an organisation centres around being able to withstand rapid environmental changes (Teece *et al*., 1997), use organisation's resources to create market changes (Eisenhardt and Martin, 2000), and at the same time being able to adjust operating routines through patterned behaviour in order to achieve improved effectiveness (Zollo and Winter, 2002). The combination of these key areas can be seen as a pointer towards achieving competitive advantage for organisations. Ambrosini and Bowman (2009) have also noted that the dynamic capabilities of an organisation influences n the organisation's resources and this, in turn, serves as the source of the firm's competitive advantage. Although some literature has characterised this theory as being vague and elusive (Kraaz and Zajac, 2001), that its nature creates difficulty in determining the merits of its outcome (Winter, 2003; Zahra *et al*., 2006), or even being repetitive (Zollo and Winter, 2002), its ability to determine sustainable competitive advantage for organisations has been appreciated (Katkalo *et al*. 2010; Wollersheima and Heimeriks, 2016).

4. Dynamic Capabilities for the attainment of competitive advantage by Construction Organisations

Although several studies have submitted diverse capabilities needed for organisations to gain competitive advantage, (Eisenhardt and Martin, 2000; Schoemaker *et al*., 2018; Teece and Pisano, 1994; Zollo and Winter, 2002), the DCT is deemed advantageous particularly for construction organisations which operate in a dynamic environment (Behm, 2008), and an ever-changing digital world (Solis, 2016). In an attempt to simplify the DCT, Teece (2007) observed three major capabilities for organisations to increase their business performance. These are the sensing, seizing and reconfiguration capabilities. Schoemaker *et al*. (2018) also acknowledged sensing, seizing and transformation as the three major pillars towards attaining dynamic capabilities. Thus, this study reviews the DCT from the sensing of digitalisation opportunities and threats, seizing digitalisation opportunities, and reconfiguring construction organisations in an attempt to promote the digitalisation of construction organisations and creating better competitive advantage in the process.

4.1 Sensing digitalisation opportunities and threats

Teece (2007) opined that as a result of the dynamic nature of the business environments, technological opportunities, as well as competitor's activities, are constantly changing. Lots of opportunities present themselves to existing business entities and new ones. However, the profit stream of the existing business tends to be more at risk in this situation than those just coming into the business. Thus, they need to have the ability to sense new opportunities and take advantage of them as quick as possible. Schoemaker *et al*. (2018) noted that it is imperative for organisations to sense market changes before their rivals do. Teece (2007) further described the sensing of opportunities as a "scanning, creating, learning, and interpretive" activity. In fact, Schoemaker *et al.* (2013) noted that if organisations are to improve their ability to sense opportunities and detect threats within the business environment, the monitoring of trends and uncertainties, and the different systems of decision making within the organisation must be strongly linked with tools for external scanning and scenario planning.

For construction organisations that aim to attain a competitive advantage through the digitalisation of its services, the ability to sense game-changing opportunities and significant threats lurking within the environment is essential. Following Teece (2007) suggestions, such construction organisation must put in place processes that will direct internal research and development (R&D) and also select new DTs that will help the organisation provide it better services. It is believed that through R&D the search for new DTs and processes can be done. This is important as it has been observed over time that construction organisations inability to embrace new technological advancement, as well as sponsoring meaningful R&D has affected the service delivery of the construction industry in most developing countries (Aghimien *et al*., 2018b; Chilipunde, 2010). Thus, if competitive advantage is to be attained through better service delivery, attention must be given to these crucial variables. Similarly, the organisations managerial and organisational processes must be structured in a way that the organisation can tap into suppliers and complementor's innovations. It has been observed that in the business environment, uncertainty abounds (Quinton *et al*., 2018). To scale through this uncertain environment, construction organisation can tap into suppliers' innovations or even mimic the innovations of those organisations within the same industry (Gutirrez *et al*., 2015). This process of mimicking others can lead to competitive advantage, considerable improvement in the use of DTs and innovations, and even development of innovative ideas based on what they have seen from others (Gutierrez *et al*., 2015; Quinton *et al*., 2018). Also, the organisation must put in place processes that will help identify target market segments, changing customers' needs, as well as customers' innovation. All this must be linked to a strong analytical system geared towards learning, sensing, filtering, shaping and calibrating opportunities (Teece, 2007).

4.2 Seizing digitalisation opportunities

Teece (2014) described seizing as the process of organising necessary resources to meet the needs and opportunities identified by sensing actions in order to maximise the value from those actions. Yeow *et al*. (2018) state that the act of seizing is crucial to the aligning of organisations with digital opportunities that have been identified using the organisation's sensing capabilities. Schoemaker *et al*. (2018) have noted that while it is important to sense opportunities, in an uncertain business environment, timely implementation of newly identified systems and innovations is crucial. In the view of Teece (2007), the act of seizing transcends beyond just understanding new opportunities. It involves the actual decision-making of specific changes needed across the organisation in order to enjoy the benefits within these identified opportunities. Other studies have also described the seizing capabilities of an organisation as the organisation's learning that is revealed through the ability to create knowledge within the organisation, obtain external knowledge, and assimilate this acquired knowledge for the creation of necessary capabilities (Cepeda and Vera, 2007; Nyachanchu *et al*., 2017). Thus, construction organisations must be conscious of the timely implementation of opportunities that they have sensed within the construction environment. Also, the process of decision making with regards to the implementation of these identified opportunities must be swift.

Following Teece (2007) suggestions, these construction organisations must create a well-defined organisational structure, procedures, designs, and incentives geared towards seizing opportunities. To achieve this, they must define the customer solution and business model of the organisation base on the knowledge acquired from sensing. This can be done through the selection of the right DTs and service style, designing of the avenue of revenue generation, selection of the target clients, and designing of the right approach towards attaining value for both the organisation and its clients. Also, selecting the right decision-making procedure, and avoiding decision error is important. Similarly, creating a clear boundary for the organisation's service is important in order to conveniently manage complements and control the organisation's service delivery. To achieve this, standardising unique assets of the organisation, controlling challenging assets, assessing appropriability, and being able to recognise and manage co-specialised economies are important. These assets as earlier identified by Teece *et al*. (1997) can be in the form of technologies, intellectual property, complementary assets, customer base, or even external relations of the organisation. Finally, in seizing opportunities, construction organisations must build loyalty and commitment. This they can achieve through quality leadership demonstration, effective communication within the organisation, with their clients, and with other project participants, and recognising non-economic factors, values, and culture (Teece, 2007).

4.3 Reconfiguring the organisation

Schoemaker *et al*. (2018) observed that in an uncertain environment, adapting to changes as they occur is not enough. Organisations may be required to reshape their activities and perhaps their ecosystems in order to enjoy the benefits of new business models. Nyachanchu *et al*. (2017) noted that the act of reconfiguring refers to the organisation's ability to create and integrate capabilities from within and outside the organisation. Teece (2007) noted that it is the constant renewal of the organisation's asset, aligning of these assets, co-alignment, and redeployment of same. This reconfiguration might require organisations to revamp their ways of conducting business, restructure units within the organisation, manage co-specialised assets, and create structures that allow knowledge development and good governance within the organisation. Yeow *et al.* (2018) summarised this as the processes of restructuring of the resources of the organisation. Rindova *et al.* (2016) noted that through the act of reconfiguring, organisations can align existing resources with newly developed strategies, and at the same time adopt new resources to augment the shortfalls of the organisational resource base. Hence, reconfiguration capabilities can be seen as the capabilities to create, and the capabilities to integrate (Nyachanchu *et al*., 2017; Pavlon and El-Sawy, 2011).

Thus, based on the clamour for construction organisations to adopt innovative processes of delivering construction projects, reconfiguring construction organisation's processes through the digitalisation of existing processes and integrating of new DTs to help improve service delivery is necessary. Following Teece (2007) suggestions, construction organisations that seek to attain competitive advantage through the digital transformation of their processes must be willing to embrace continuous alignment and realignment of their tangible, and intangible assets with what is obtainable within the digital world. Such an organisation must be able to decentralise its activities by embracing open innovation and developing its integration and coordination skills. Also, effective knowledge management is important. Continuous learning of the use of evolving DTs, transferring of knowledge gained, and integrating such knowledge into the services of the organisation is crucial.

5. Lessons Learnt

It is evident that the construction industry operates in a very competitive and dynamic environment. Advancement in technologies has made this environment even more competitive as everyday organisations strive to be innovative through the use of diverse technologies in a bid to deliver better services to their client and attain a competitive edge over their competitors. In this dynamic world of technology with DTs evolving by the day, construction organisations must evolve in terms of the dynamic capabilities needed to withstand these changes. Following the DCT, it is believed that the ability of a construction organisation to be digitalised could be considered as an organisation's dynamic capability in itself. This is because the ability of an organisation to be digitised complements the organisation's digital orientation since only organisations that have the skills to effectively manage new DTs will readily adopt same and make good use of them in the delivery of new products (Khin and Ho, 2018). Thus, having the capability to implement and manage digitalisation within the organisation is the first key dynamic capability for construction organisations gunning for sustained competitive advantage attained through digitalisation. Studies have further proven that if construction organisations are to attain competitive advantage, then they must attain dynamic capabilities in terms of their ability to sense, seize, and reconfigure (Schoemaker *et al*., 2018; Teece, 2007). Construction organisation must possess the capability to identify digitalisation opportunities and threats earlier than its competitors. This can be attained through investment in R&D, careful selection of DTs that will help in innovative service delivery, structuring managerial and organisation processes to be able to tap into suppliers and complementor's digital innovations, ability to target the most suitable market segments, understand changing clients' needs, and clients' innovation (Teece, 2007).

Similarly, based on what has been sensed within the environment, the timely implementation must be carried out (Schoemaker *et al*., 2018). Construction organisations must be quick to learn from what they have sensed within the environment and utilise the knowledge gathered to the fullest. Swift decision-making with regards to the implementation of the identified opportunities is key (Nyachanchu *et al*., 2017; Teece, 2014; Yeow *et al.*, 2018). To adequately seize opportunities, construction organisations must consider the selection of the right DTs and service style to be adopted, design the mode of revenue generation, select the target clients, design the right approach towards attaining value for both the organisation and its clients, select the right decision-making procedure, avoid decision errors, standardise unique assets, control challenging assets, assess appropriability, recognise and manage co-specialised economies, demonstrate quality leadership, promote effective communication with all parties, and recognise non-economic factors (Teece, 2007). Construction organisations must also be ready to restructure their organisational resources in order to conform to the changing environment. The continuous alignment and realignment of tangible and intangible assets with what is obtainable within the digital world are necessary (Rindova *et al.*, 2016; Schoemaker *et al*., 2018; Teece, 2014; Yeow *et al*., 2018). This can be achieved through decentralising organisation's activities by embracing open innovation, developing organisation's integration and coordination skills, effectively managing knowledge, continuous learning of the use of evolving DTs, transferring and integrating knowledge gained into the services of the organisation (Tecee 2007).

6. Conclusion

No doubt the 4IR is upon us with evidence of its adoption is emanating within diverse industries. Digitalisation which is a key driver of the 4IR promises immense benefits to both its adopters and their customers. However, the world of DTs is not constant as new development abounds on a continuous basis. Thus, organisations that wish to survive in this ever-changing environment must be conscious of the dynamic capabilities needed to achieve this feat. Firstly, if construction organisations are to stay competitive and even attain a competitive advantage over their counterparts, they must be ready to adopt and implement DTs in their service delivery. This is crucial as studies have proven that the construction industry is among the least industry to imbibe the digitalisation culture. Secondly, these organisations must grow their dynamic capabilities in the area of sensing of opportunities and threats within their environment, seizing of sensed opportunities, and reconfiguring of their organisational resources to conform with the ever-changing environment. Important variables worth noting include investment in R&D, careful selection of DTs, tapping into suppliers and complementor's digital innovations, understand changing clients' needs, selection of the right DTs and service style, selection of the target clients, designing the right approach towards attaining value, selecting the right decision-making procedure, avoiding decision errors, standardising unique assets, controlling challenging assets, demonstrating quality leadership, promoting effective communication with all parties, decentralising organisation's activities by embracing open innovation, developing organisation's integration and coordination skills, effectively managing knowledge, continuous learning of the use of evolving DTs, transferring and integrating knowledge gained into the services of the organisation.

This study contributes to the body of existing knowledge on the digital transformation of the construction industry as it provides possible direction towards attaining digitalisation through the dynamic capability of construction organisations. It is believed that its findings can serve as a starting point for the awakening of construction organisations that seek to gain a competitive advantage over their competitors through the digitalisation of their services. However, it imperative to note that the study those not claim that the attainment of competitive advantage through digitalisation only lies in the variables identified as some other external factors not covered within the DCT may influence same. Therefore, further empirical studies are needed to confirm the identified dynamic capabilities as they apply within the construction organisations and to also unearth other salient variables that were not mentioned in the literature earlier reviewed.

Acknowledgements

The authors would like to acknowledge the support of the South Africa National Research Fund and the University of Johannesburg.

References

Agarwal, R., Chandrasekaran, S. & Sridhar, M (2016). *Imagining Construction's Digital Future. Capital Project and Infrastructure*, Mckinsey And Company. Available on: Https://Www.Mckinsey.Com/Industries/Capital-Projects-And-Infrastructure/OurInsights/Imagining-Constructions-Digital-Future.

Aghimien, D. O, Aghimien, E. I., Fadiyimu, A. O. & Adegbemo, T. F. (2018a). Survival Strategies for Construction Related Organisations in a Challenging Economy. *Engineering, Construction and Architectural Management*, 25(7), 861-876

Aghimien, D. O, Aigbavboa, C. O, & Oke, A. E. (2018b). Digitalisation for Effective Construction Project Delivery in South Africa. *Contemporary Construction Conference: Dynamic and Innovative Built Environment (CCC2018), Coventry United Kingdom, 5-6 July 2018* p. 3-10

Ambrosini, V. and Bowman, C. (2009). What are dynamic capabilities and are they a useful construct in strategic management? *International Journal of Management Reviews*, 11(1), 29-49.

Ashcraft H., (2007). *Building Information Modeling - collaboration for construction lawyers*. http://hbmvr.com/docs/articles/bimbuildinginformationmodellingaframework

Bahrin, M.A.K., Othman, M.F., Nor, N.H. & Azli, M.F.T. (2016). Industry 4.0: A Review on Industrial Automation and Robotic, *Jurnal Teknologi (Sciences and Engineering)*, 137–143.

Behm, M. (2008). The Construction Sector; Rapporteur's Report; East Carolina University, *Journal of Safety Research* 39; 175–178

Bienhaus, F. & Haddud, A. (2018). Procurement 4.0: factors influencing the digitisation of procurement and supply chains. *Business Process Management Journal*, 24(4), 965-984.

Castagnino, S., Rothballer, C. & Gerbert, P. (2016). What's the future of the construction industry? World Economic Forum. Available on: https://www.weforum.org/agenda/2016/04/building-in-the-fourth-industrial-revolution/

Celaschi, F., (2017). Advanced design-driven approaches for an industry 4.0 framework: The human-centred dimension of the digital industrial revolution. *Strategic design research journal*, 10(2), 97-104

Cepeda, G., & Vera, D. (2007). Dynamic capabilities and operational capabilities: A knowledge management perspective. *Journal of Business Research*, 60(5), 426-437.

Chen, T., Wang, Y., Nevo, S., Jin, J., Wang, L. & Chow, W.S. (2014). IT capability and organizational performance: the role of business process agility and environmental factors. *European Journal of Information Systems*, 23(3), 326–342

Chilipunde, R.L. (2010). *Constraints and Challenges Faced By Small, Medium And Micro Enterprise Contractors In Malawi*. A treatise submitted to the Faculty of Engineering, the Built Environment and Information Technology, Nelson Mandela Metropolitan University, School of the Built Environment

Crampton, N. (2017). What is Digitalisation and what does it mean for your business? Available from: https://bizconnect.standardbank.co.za/sector-news/construction/the-digitalisation-of-the-construction-industry.aspx.

De Andrade Régio, M.M., Gaspar, M.R.C., Do Carmo Farinha, L. M., & De Passos Morgado, M.M.A. (2016). Forecasting the disruptive skillset alignment induced by the forthcoming industrial revolution. *Romanian review precision mechanics, optics & mecatronics*, 49, 24-29

Dimick, S. (2014), Adopting Digital Technologies: The Path for SMEs. Ottawa: *The Conference Board of Canada*, 1-13

Eisenhardt KM, Martin JA (2000) Dynamic capabilities: What are they? *Strategic Management J*. 21(10–11), 1105–1121

Gutierrez, A., Boukrami, A., and Lumsden, R. (2015). Technological, organisational and environmental factors influencing managers’ decision to adopt cloud computing in the UK. *Journal of Enterprise Information Management*, 28(6), 788-807

Ibem E. O. & Laryea S. (2014). Survey of digital technologies in procurement of construction projects. *Automation in Construction*, 46, 11-21

Kalavendi, R. (2017). Digitisation and Digitalisation: The two-letter difference. Available on: https://medium.com/@ravisierraatlantic/digitization-digitalization-the-2-letter-difference-59b747d42ade

Katkalo V.S., Pitelis C.N., & Teece D.J. (2010). Introduction: On the nature and scope of dynamic capabilities. Indust. Corporate Change 19(4),1175–1186.

Khin, S., & Ho, T.C.F. (2018). Digital technology, digital capability and organizational performance: A mediating role of digital innovation. *International Journal of Innovation Science*, early cite.

Kraaz, M. and Zajac, E. (2001). How organizational resources affect strategic change and performance in turbulent environments: theory and evidence. *Organization Science*, 12(5), 632-57.

Kumar, P. & Ravali, K. (2012). Going green with cloud computing. *Bookman International Journal of Software Engineering*, 1(1), 31-33

Lim, S., Buswell, R.A., Le, T.T., Austin, S.A., Gibb, A.G.F., & Thorpe, T. (2012). Developments in construction-scale additive manufacturing processes. *Automation in Construction*, 21, 262–268

McLaughlin, S. (2017). Dynamic capabilities: taking an emerging technology Perspective. *Int. J. Manufacturing Technology and Management,* 31(1/2/3) 62-81

Navon, R. (2005). Automated Project Performance Control of Construction Projects. *Automation in Construction*, 14, 467-476.

Noor, T., Sheng, Z., Zeadally, S. & Yu, J. (2013). Trust management of services in cloud environments: obstacles and solutions. *ACM Computing Surveys*, 46(1), 12-30.

Nyachanchu, T.O., Chepkwony, J. & Bonuke, R. (2017). Role of Dynamic Capabilities in the Performance of Manufacturing Firms in Nairobi County, Kenya. *European Scientific Journal November*, 13(31), 438-454

Ochs, T. & Riemann, U. T. (2018). IT Strategy Follows Digitalisation. Encyclopaedia of Information Science and Technology, Fourth Edition

Oke, A.E. & Ogunsemi, D.R. (2011). Value management in the Nigerian construction industry: militating factors and perceived benefits. *Proceeding of the second International Conference on Advances in Engineering and Technology*, Faculty of Technology, Makerere University, Uganda, 30 January - 1 February, 353-359.

Osunsanmi, T. O., Aigbavboa, C. O. & Oke, A. E. (2018). Construction 4.0: The Future of South Africa Construction Industry. *World Academy of Science, Engineering and Technology International Journal of Civil and Environmental Engineering*, 12, (3), 206-212

Ozlu, F. (2017). The advent of turkey's industry 4.0. *Turkish policy quarterly*, 16(2), 29-38.

Pavlou, P. A., & El Sawy, O. A. (2011). Understanding the elusive black box of dynamic capabilities. *Decision Sciences*, *42*(1), 239-273.

Petrillo, A., De Felice, F., Cioffi, R., &Zomparelli, F., (2018). Fourth Industrial Revolution: Current Practices, Challenges, and Opportunities, in Digital Transformation in Smart Manufacturing Digital Transformation in Smart Manufacturing, In Antonella Petrillo, Raffaele Cioffi and Fabio De Felice, Intech. Available from: https://www.intechopen.com/books/digital-transformation-in-smart-manufacturing/fourth-industrial-revolution-current-practices-challenges-and-opportunities

Quinton, S., Canhoto, A., Molinillo, S., Pera R. & Budhathoki, T. (2018). Conceptualising a digital orientation: antecedents of supporting SME performance in the digital economy, *Journal of Strategic Marketing*, 26(50), 427-439

Rindova, V.R., Martins, L., Yeow, A. (2016). The Hare and the Fast Tortoise: Dynamic Resource Reconfiguration and the Pursuit of New Growth Opportunities by Yahoo and Google (1995–2007). In: *Folta, T., Helfat, C.E., Karim, S. (Eds.), Advances in Strategic Management (Resource Redeployment and Corporate Strategy)*, 253–284.

Schoemaker, P.J.H., Day, G.S. & Snyder, S.A. (2013). Integrating Organizational Networks, Weak Signals, Strategic Radars and Scenario Planning. *Technological Forecasting & Social Change*, 80(4), 815-824.

Schoemaker, P.J.H., Heaton, S. & Teece, D.J. (2018). Innovation, Dynamic Capabilities, and Leadership. *California Management Review*, 6(1), 15-42

Solis, B. (2016). The Six Stages of Digital Transformation Maturity. Altimeter Cognizant.

Teece, D. (2007). Explicating dynamic capabilities: the nature and microfoundations of sustainable enterprise performance. Strategic Management Journal, 28(8), 1319-1350

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic Capabilities and Strategic Management. *Strategic Management Journal*, *18*(7), 509-533.

Teece, D.J. & Pisano, G. (1994). The Dynamic Capabilities of Firms: An Introduction. *Working Paper for the International Institute for Applied Systems Analysis*, 1-34

Teece, D.J., (2014). The foundations of enterprise performance: dynamic and ordinary capabilities in an (economic) theory of firms. *Acad. Manage. Perspect*. 24 (4), 328–352.

Vaidya, S., Ambad, P., & Bhosle, S. (2018). Industry 4.0: A glimpse. *Procedia manufacturing*, 20(11-12), 233-238.

Winter, S. (2003). Understanding dynamic capabilities. *Strategic Management Journal*, 24(10), 991-5.

Wollersheim, J. & Heimeriks, K.H. (2016) Dynamic Capabilities and Their Characteristic Qualities: Insights from a Lab Experiment. *Organization Science,* 1-16

Yeow, A., Soh, C. & Hansen, R. (2018). Aligning with new digital strategy: A dynamic capabilities approach. *Journal of Strategic Information Systems* 27, 43–58

Zahra, S., Sapienza, H.J. and Davidsson, P. (2006). Entrepreneurship and dynamic capabilities: a review, model and research agenda. *Journal of Management Studies*, 43(4), 917-55.

Zhou, K.Z. & Li, C.B. (2010). How strategic orientations influence the building of dynamic capability in emerging economies. Journal of Business Research 63, 224–231

Zollo, M. and Winter, S.G. (2002). Deliberate learning and the evolution of dynamic capabilities. *Organization Science*, *13*(3), 339-351.

Viewing Digitalisation in Construction through the Lens of Past Studies

Douglas Aghimien[1, *], linton Aigbavboa[1], Ayodeji Oke[1]
[1] SARChi in Sustainable Construction Management & Leadership in the Built Environment, Faculty of Engineering and the Built Environment, University of Johannesburg, South Africa
* email: aghimiendouglas@yahoo.com

Abstract

With the fourth industrial revolution come issues surrounding the digitalisation of the construction business. While studies on the digital transformation of industries such as manufacturing, banking, telecommunication, education, and the likes continue to emerge, the story is not the same for construction. The industry has been known for its slow adoption of digital technologies and paucity of information exists in the area of its digitalisation. It is based on this notion that this study conducted a bibliometric review of digitalisation research in construction-related fields with a view to understanding the area of focus of past studies. Data used were gathered from Scopus database (conferences and Journals), and only materials with digitalisation/digitisation/digital transformation and construction in their title, abstract and/or keywords were extracted for further assessment. VOSviewer was used to prepare a co-occurrence map based on the bibliographic data gathered. Findings revealed that increase publication on digitalisation started in 2015, most of which exists in conference proceedings. Majority of these publications emanated from Asian and European countries, with none evident within African countries. Research on digitalisation within construction-related fields have placed focus on construction project delivery, BIM and project design, the digital transformation of the construction industry, and BIM in construction project management. Furthermore, the current research focus is tending towards more of modeling of information to deliver the best possible construction. This study contributes to the body of knowledge as it reveals areas for possible research in digitalisation in construction, particularly in African countries were lack of literature in this regard exist.

Keywords: Construction, Digitisation, Digitalisation, Digital technologies, Digital transformation

1. Introduction

Technological advancements are increasing at an alarming rate, thus, constantly altering the way in which the society lives and functions. One such advancement is the fourth industrial revolution (4IR) which incorporates the use of digital technologies (DTs) and processes in a bid to achieve more efficient service delivery. Evidence of this has been noted within the manufacturing industry (Dall'Omo, 2017; De Carolis *et al.,* 2017), banking sector (Mladenovic, 2018), education sector (Sheikhshoaei *et al.*, 2017), telecommunication (Khin and Ho, 2018; Valdez-de-Leon, 2016) etc., of most developed and some developing countries around the world. Traces of the adoption of the concept of 4IR are equally becoming evident within the construction industry of developed countries and immense benefits are promised. However, the situation is different for most developing countries as their construction industries faces diverse challenges that impede the adoption of new concepts (Aghmien *et al*., 2018).

It has been observed that digitalisation is a key driver of the 4IR (Bienhaus and Haddud, 2017). However, it is imperative to state at this point that the word "digitalisation" has come with diverse meaning since the advent of the 4IR. Words such as digitisation, digitising, and digital technology, have been used in place of digitalisation. In most cases, these exchanges have been made wrongly (I-Scoop, 2016). Rouse (2017) viewed the term "digitisation" as the process of transforming information into digital format. I-Scoop (2016) described digitisation as simply the conversion and/or representation of something non-digital into a digital format, which can then be used by a computing system for diverse purposes. On the other hand, the term "digitalisation" according to Kalavendi (2017) is the increased use of DTs in the operations of an organisation. Simply put, digitalisation is the incorporation of DTs into everyday life, through digitising anything that is capable of being digitised (Ochs and Riemann, 2018). Thus, while digitisation is seen as the digital transformation of specific processes that were not originally digital, through the use of DTs, digitalisation is the deployment of these transformed processes into the business life of the organisation. Based on the aforementioned descriptions, in the context of this study, the term digitalisation is conceptualised as *the innovative use of digital technologies in the delivery of tangible and intangible services within a construction organisation with a view to gaining a competitive advantage over other competitors and provide better service delivery*.

Despite the immense benefits that come with the digitalisation of services, the adoption of DTs in the construction is still slow in most developing countries (Building Radar, 2015; Castagnino *et al.*, 2016; Osunsanmi *et al*., 2018). One key culprit of this lack of adoption is the lack of investment in research and development (R&D) (Aghimien *et al*., 2018). Aghimien *et al.*, (2019), Chilipunde (2010), and Fadhi and Tan (2001) all noted that the construction industry in developing countries rarely supports R&D and this has significantly affected the industry's development particularly in the aspect of adopting innovative technologies. This shortcoming is bound to affect the knowledge and understanding of the existence and applicability of available DTs needed for the attainment of digitalisation of the industry. It is based on this knowledge that this study set out to identify research focus in digitalisation within construction-related fields.

2. Overview of Digitalisation in Construction

Digitalisation is described as the most important current technological advancement, whose impact will be faced by all levels of society (Leviakangas *et al*., 2017). Dall'Omo (2017) observed that digitalisation has found an abode in every aspect of human life, be it simple personal devices or complex industrial systems. Ochs and Riemann (2018) noted that digitalisation incorporates digital technologies into everyday life, through digitising anything that can be digitised. According to Leviakangas *et al.* (2017), a unique technological base for metasystems of products is created through the use of DTs such as intelligent sensors, robotics, and automation. Rüßmann *et al.* (2015) highlighted some significant DTs that are driving the 4IR. Examples include Building Information Modeling (BIM) which is described as "utilises cutting-edge digital technology to establish a computable representation of all the physical and functional characteristics of a facility and its related project life-cycle information, and it is intended to be a repository of information for the facility owner/operator to use and maintain throughout the life-cycle of a facility" (Ashcraft, 2007). There is also the Internet of Things (IoT) which is an overall system of network, linked to each other and uniformly addressed objects by means of standard conventions (Vaidya *et al.*, 2018); augmented reality, which is an innovation that gives an augmented view of objects or designs using specific gadgets (Celaschi, 2017); and big data analytics which is viewed as the most vital technology in relation to the large collection, preparation, and investigation of unorganised and organised information with savvy algorithms (Petrillo *et al*., 2018). There is also the use of autonomous robots in performing autonomous production (Bahrin *et al.*, 2016), cloud computing wherein scalable IT-related capabilities are provided as a service over the internet to multiple external customers (Kumar and Ravali, 2012), 3D printing which is the process of creating a physical object from a 3D digital model in a layer by layer process (Lim *et al.,* 2012), and many other technologies which are gradually gaining recognition within the construction industry.

It has been noted that for digitalisation to be attained, structures within an organisation, management views, as well as organisations business strategies need to be transformed digitally. Matt *et al.* (2015) noted that organisations that desire to be digitally transformed needs to formulate a strategy that will cut across other business strategies and allows management to properly coordinate business activities, identify priorities, implement and at the same time oversee transformations that occurs as a result of new technologies. Despite the immense contribution digitalization proposes to the development of construction organisations, these organisations still face challenges that deter their digital transformations. Examples of these challenges include; lack of technical know-how (Bédard-Maltais, 2017), expensive associated cost of implementation and training of workers (Oke *et al*., 2018), data security issues (Redmond *et al*., 2012; Zeng *et al*., 2012) issue of interoperability (Eastman *et al*., 2011), and fear and resistance to new technologies (Bédard-Maltais, 2017) just to mention a few. Thus, for the successful attainment of the strategies for the transformation of organisations through the use of new technologies as suggested by Matt *et al.* (2015), construction organisations need to first solve the existing problems that may obstruct their smooth transitioning into becoming a digitalised organisation

3. Research Methodology

The study assessed the areas of research focus in published works on digitalisation within construction-related fields. Due to the newness of the concept of digitalisation in construction, a bibliometric technique which according to Olawumi and Chan (2018) allows a concise identification and mapping of scientific knowledge area through the identification of research patterns and boundaries, was adopted. A literature search was conducted using the Scopus database which has been identified as one of the major databases that cover different scientific fields (Guz and Rushchitsky, 2009). Since its introduction in 2004 by Elsevier Science, Scopus has rapidly become a leading choice for literature search and has been adopted in most review works (Chadegani *et al*., 2013). Also, Olawumi *et al.* (2017) have earlier noted that no clear distinction exists between Scopus and Web of Science which is considered as the two major science research databases. It was further stated that there exists considerable overlap in the records of both databases. While the study of Olawumi *et al.* (2017), assessed BIM literature using information gathered from the web of science, the study of Vuksic *et al.* (2018) on digital transformation case studies adopted information from both Scopus and Web of Science. This current study, however, focused on research works from Scopus which is a more recent and fast-growing database recognised among scientific researchers as observed by Chadegani *et al*. (2013).

The search for relevant literature focused on published journal articles and conference proceedings within construction-related study areas. More specifically, these study areas include engineering (which include construction), energy, material science, environmental science, and business management. The choice of selecting journal articles was premised on the fact that articles from journals are considered more reliable sources of knowledge and are deemed more concise and detailed than other sources of information (Zheng *et al.,* 2016). Similarly, Webster and Watson (2002) have earlier recognised the importance of conference proceedings as reliable sources of literature review, hence their inclusion in this study. A similar approach was taken by Vuksic *et al.* (2018). The key search words adopted for the study were “digitalisation” AND Construction, “digitisation” AND Construction, and “digital transformation” AND Construction. Only research having these search words in their title, abstracts and keywords were considered for review. In searching, no restriction was placed on the range for publication year due to the assumption that digitalisation is only becoming a recent concept within the construction industry. Thus, placing a restriction on year might significantly reduce the number of revealed literature. Only articles published in the English language were considered and the literature search was conducted in January 2019. The initial search using the stated keywords revealed a total of 116 articles published between 1981 and 2019. After careful analysis of the papers extracted, 2 were deleted due to repetition leaving a total of 114 articles.

The results are presented based on co-occurrence in terms of a number of publications per year, the number of publications per country, and the co-occurrence of keywords. A co-occurrence map was developed based using VOSviewer which is literature review software that offers the basic functionality needed for visualising bibliometric networks in the easiest way possible. The software displays only the nodes in a bibliometric network and in its visualisation (Van Eck and Waltman, 2014).

4. Results and Discussions

4.1 Publication per year

The result in figure 1 reveals the number of articles published from 1981 to 2019. From the figure, it is clear that from 1981 up to 2014 less research emanated around issues on digitalisation. This result can be attributed to the fact that the concept of digitalisation became stronger with the advent of 4IR which was first established at the Hannover Fair in 2011 in Germany (Sung, 2018). Since then, issues surrounding 4IR have become topical in most industries (Crnjac *et al.*, 2017). Interestingly, Bienhaus and Haddud (2017) have earlier noted that digitalisation features such as the Internet of Things, Industrial Internet of Things, cloud based manufacturing, and smart manufacturing are important drivers of 4IR. Thus, with the focus on 4IR came the research attention on digitalisation. A significant rise is evident in the year 2015 with 6 publications higher than the 3 observed in 2014. In 2016, a drop from 9 publications experienced in 2015 to 7 publications can be seen. 2017 saw an enormous increase from 7 publications in 2016 to 19, and this continued into 2018 were 27 publications were derived. The year 2019 has recorded 1 research so far and this was because the review was done in the first month (January) of the year. It is believed that more researches will emanate as the year goes by. The finding of this study is similar to the submission of Reis *et al.* (2018) and Vuksic *et al.* (2018) that discovered an increase in literature on digital transformation from 2016 to 2018. In terms of the type of publication, the result revealed that 75 out of the 114 extracted articles came from conferences, while the remaining 39 were journal articles. This can be as a result of the rigor and long duration taken in the publication process of journal articles when compared to conferences papers.

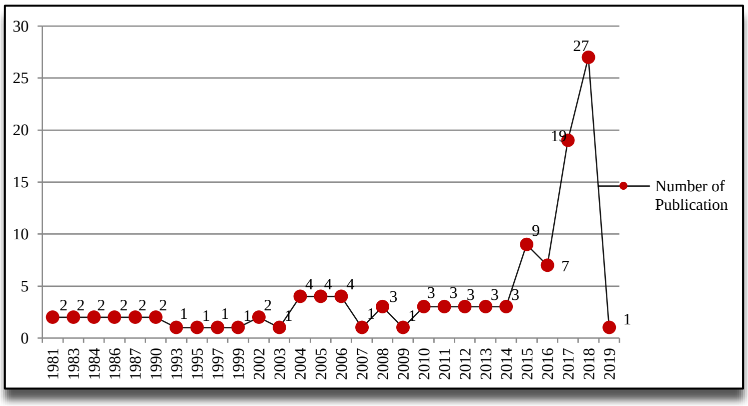


Figure 1: Publications per publication year

4.2 Publication per country

Assessing the number of articles per country of origin, the result revealed that the 114 extracted papers emanated from 28 different countries, of which 13 had just 1 publication each. Figure 2 shows the list of countries with at least 2 publications. China tops this list with 23 research articles. This is followed by Germany, the USA and the United Kingdom with 13, 12 and 8 articles respectively. Sweden, Italy, and South Korea all shared the fifth position with 7 articles each. This implies that most articles on digitalisation in construction-related fields emanated from Asia and European countries. This submission is in tandem with the submissions of Olawumi *et al.* (2017) who noted that most research on BIM (a crucial digitalisation feature) published between 1990 and 2016 emanated from Asia and Europe. The findings are also in line with that of Vuksic *et al.* (2018) which noted that digital transformation research is more from European countries (such as Germany and Baltic), USA and Canada. However, while Canada revealed a considerable number of literature in their study, it revealed only one in this current study. Reason for this disparity can be associated with the difference in the database used in both studies. Findings of this study are also consistent with the Institute of Management Development (IMD) “world digital competitiveness” ranking which revealed that the top 10 most digitally competitive countries in the world are USA, Canada, Hong Kong, and 7 European countries (IMD, 2018). A look at the figure revealed that there is no study emanating from Africa. This shows a knowledge gap in the area of digitalisation in Africa.

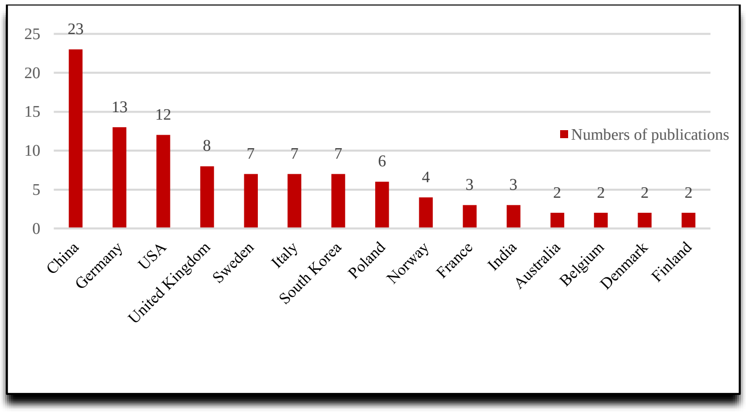


Figure 2: Publications per country

4.3 Co-Occurring Keywords

Using VOSviewer, a co-occurrence map was created. With the minimum number of co-occurrence of keywords set at 5 (VOSviewer default), out of a total number of 1296 Keywords generated, 22 co-occurred 5 times. These 22 co-occurring keywords were grouped into 4 clusters. It is important to note that the closer the keywords to each other the higher their co-occurrence (Van Eck and Waltman, 2014). A look at Figure 3 shows that **Cluster 1** which is the red region has keywords such as construction industry, construction projects, computer-aided design, product design, information technology, and automation. This cluster can be seen as keywords relating to *Construction project delivery*. **Cluster 2** which is represented in green has keywords such as architectural design, BIM, information theory, structural design, and construction. This cluster considers issues relating to *BIM and Project Design*. **Cluster 3** which is represented in blue shows keywords such as analogue to digital conversion, digitisation, digital technologies, information management, and life cycle. This cluster is seen to encompass issues relating to *digital transformation*. **Cluster 4** which is the last cluster is seen in yellow and has keywords such as BIM and project management. It is clear that this cluster focuses on the use of *BIM in construction project management*. Base on the co-occurrence of these keywords, it is evident that researches on digitalisation in construction-related fields have placed focus on applying digitalisation concepts for the successful delivery of construction projects, adopting BIM for the designing of construction projects, the digital transformation of construction activities, and using BIM for effective project management. This finding further confirms Ibem and Laryea (2014) assertion that BIM has made the use of DTs a popular concept within the construction industry. This is because the findings revealed a major emphasis on BIM in past studies. Olawumi *et al.* (2017), Kovacic *et al.* (2015), and Won *et al.* (2013) all noted that the attention being given to BIM in the construction industry is as a result of its ability to provide easy use and reuse of project data across the project development phases. At the same time, it prevents unnecessary replication of project or design tasks.

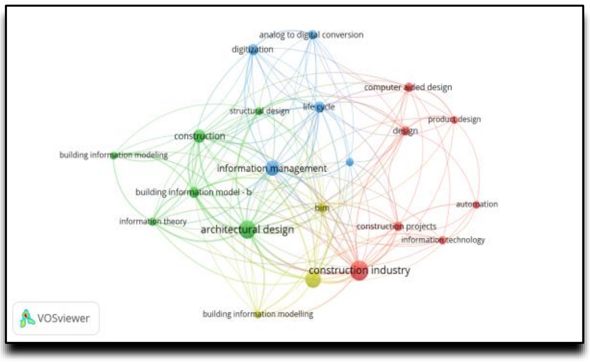


Figure 3: Network visualisation map for co-occurring keywords

Figure 4 is the overlay visualisation map generated from VOSviewer showing the different co-occurring keywords in the different years. With a threshold of 5 occurrences, it is evident that the identified keywords started co-occurring from 2013 with words such as analogue to digital conversion, design, and automation being evident. This means that as of 2013, digitalisation researches were concentrating on the conversion of some basic function from analogue to digital, and the use of automation for project delivery. The year 2014 saw keywords such as structural design, computer-aided design, and product design co-occurring. This implies that in that year, more attention was placed on using these digital conversions in designing construction projects. Researches in 2015 were more on construction information management related, with keywords such as construction industry, information management, and information theory being evident. In 2016 more issues on project management were evident. Keywords such as project management, construction, digitisation, lifecycle, architectural design, BIM can be seen to co-occur. This co-occurrence of BIM continued into 2017 up on-till 2018 as BIM and DTs are the evident keywords.

This review shows that the trend in digitalisation researches within construction-related fields has earlier involved viewing digitalisation in terms of the transforming of construction-related activities into digital formats, and the usage of digital tools for construction project design. From then on, research has placed focus on effective management of the enormous information emanating from construction projects in order to deliver successful projects. From the management of information, research focus on modeling this information through the use of DTs to deliver best possible construction projects is now evident.

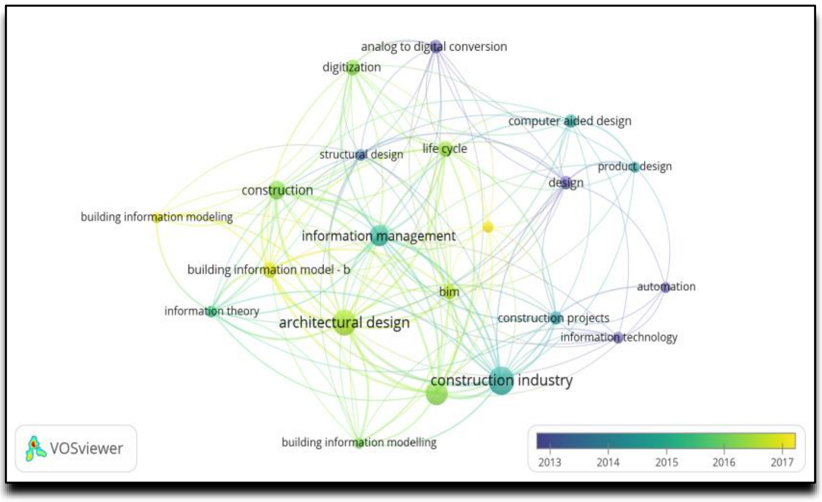


Figure 4: Overlay visualisation map

5. Conclusion

Based on the extracted studies published and indexed in the Scopus database, the study has been able to identify the key area of concentration in research relating to digitalisation within the construction-related fields. The findings have revealed that increase publication on digitalisation started in 2015, most of which exists in conference proceedings. Majority of these publications emanated from Asian and European countries such as China, Germany, USA, and the United Kingdom, with none evident within African countries. Based on the different clusters extracted, research on digitalisation within construction-related fields have placed focus on construction project delivery, BIM and project design, digital transformation, and BIM in construction project management. Furthermore, current research focus in this area is tending towards modeling of information to deliver the best possible construction projects. It can be concluded that there exists a knowledge gap in African countries in terms of researches on digitalisation of their construction industry. Researchers can, therefore, seize the opportunity to add significantly to the body of knowledge with regard to the digitalisation of the construction industry in Africa. Similarly, findings of this study have revealed that while several DTs are driving the 4IR, BIM is given more attention within the construction-related fields. While the use of BIM is good, a holistic digital transformation of the construction industry can only be attained when diverse DTs are put together for effective service delivery. Thus, more focus needs to be placed on other DTs and how they can better improve the delivery of construction projects particularly in developing countries where construction projects have been adjudged as being poor.

This study contributes significantly to the body of knowledge on digitalisation in construction as it reveals areas wherein research focus has been placed on issues relating to digitalisation within construction-related fields. Its findings have also mapped out possible areas for research in digitalisation in construction particularly in African countries were lack of literature in this regard exist. However, while this study contributes immensely to the body of existing literature on digitalisation, care must be taken in generalising its results since data used were gathered from only Scopus database. Although significant overlap is believed to exist between Scopus and some other databases, further studies can be conducted using other databases or the combination of several others in order to compare results and have a broader view of the research topic.

Acknowledgements

The authors would like to acknowledge the support of the South Africa National Research Fund and the University of Johannesburg.

References

Aghimien, D. O, Aigbavboa, C. O, & Oke, A. E. (2018). Digitalisation for Effective Construction Project Delivery in South Africa. *Contemporary Construction Conference: Dynamic and Innovative Built Environment (CCC2018), Coventry United Kingdom, 5-6 July 2018* p. 3-10

Aghimien, D., Aigbavboa, C., & Oke, A. (2019). A Review of the Application of Data Mining for Sustainable Construction in Nigeria. *Energy Procedia*, 158, 3240-3245

Ashcraft H., (2007). *Building Information Modeling - collaboration for construction lawyers*. http://hbmvr.com/docs/articles/bimbuildinginformationmodelingaframework

Bahrin, M.A.K., Othman, M.F., Nor, N.H. & Azli, M.F.T. (2016). Industry 4.0: A Review on Industrial Automation and Robotic, *Jurnal Teknologi (Sciences and Engineering)*, 137–143.

Bédard-Maltais, P. (2017). Industry 4.0: The New Industrial Revolution - Are Canadian manufacturers ready? BDC Study. Available on: https://www.bdc.ca/EN/Documents/analysis.../bdc-resume-etude-manufacturing-en

Bienhaus, F. & Haddud, A. (2018). Procurement 4.0: factors influencing the digitisation of procurement and supply chains. *Business Process Management Journal*, 24(4), 965-984.

Building Rader (2015). Digitalisation of the construction industry: Building Information Modeling. Construction Data, Construction industry market research. Available on: ttps://buildingradar.com/construction-blog/building-information-modeling/

Castagnino, S., Rothballer, C. & Gerbert, P. (2016). What's the future of the construction industry? World Economic Forum. Available on: https://www.weforum.org/agenda/2016/04/building-in-the-fourth-industrial-revolution/

Celaschi, F. (2017). Advanced design-driven approaches for an industry 4.0 framework: The human-centred dimension of the digital industrial revolution. *Strategic design research journal,* 10(2), 97-104

Chadegani, D.A.A., Salehi, H., Yunus, M.M., Farhadi, H., Fooladi, M., Farhadi, M., and Ebrahim, N.A. (2013). A Comparison between Two Main Academic Literature Collections: Web of Science and Scopus. *Asian Social Science*, 9(5), 18-26

Chilipunde, R .L. (2010). *Constraints and Challenges Faced By Small, Medium And Micro Enterprise Contractors In Malawi.* A treatise submitted to the Faculty of Engineering, the Built Environment and Information Technology, Nelson Mandela Metropolitan University, School of the Built Environment

Crnjac, M., Veža, I., & Banduka, N. (2017). From Concept to the Introduction of Industry 4.0. International Journal of Industrial Engineering and Management (IJIEM), 8(1), 21-30

Dall'Omo, S. (2017). Driving African development through smarter technology. *African Digitalisation Maturity Report*, p.1-45

Eastman, C., Teicholz, P., Sacks, R., & Liston, K., (2011). BIM Handbook – A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, 2nd Edition. Wiley

Fadhil, M. D., and Tan, F. H. (2001). Developing World Class Construction Companies in Singapore. *Construction Management and Economics*. 19(6), 591-599.

Guz, A. N., & Rushchitsky, J. J. (2009). Scopus: A system for the evaluation of scientific journals. *International Applied Mechanics*, 45(4), 351-362.

Ibem E. O. & Laryea S. (2014). Survey of digital technologies in procurement of construction projects. *Automation in Construction*, 46, 11-21

Institute of Management Development (IMD) (2018). *World Digital Competitiveness Ranking*. Available on: https://www.imd.org/wcc/world-competitiveness-center-rankings/world-digital-competitiveness-rankings-2018/

I-Scoop (2016). *Digitization, digitalization and digital transformation: the differences*. Available on: https://www.i-scoop.eu/digitization-digitalization-digital-transformation-disruption/

Kalavendi, R. (2017). *Digitisation and Digitalisation: The two-letter difference*. Available on: https://medium.com/@ravisierraatlantic/digitization-digitalization-the-2-letter-difference-59b747d42ade

Khin, S., & Ho, T.C.F. (2018). Digital technology, digital capability and organizational performance: A mediating role of digital innovation. *International Journal of Innovation Science,* early cite.

Kovacic, I., Filzmoser, M., Kiesel, K., Oberwinter, L., & Mahdavi, A. (2015). BIM teaching as support to integrated design practice. *Građevinar* 67 (6), 537-546

Kumar, P. & Ravali, K. (2012). Going green with cloud computing. *Bookman International Journal of Software Engineering,* 1(1), 31-33

Leviakangas, P., Paik, S. M., & Moon, S. (2017). Keeping up with the pace of digitization: The case of the Australian construction industry. *Technology in Society*, 50, 33 - 43

Lim, S., Buswell, R.A., Le, T.T., Austin, S.A., Gibb, A.G.F., & Thorpe, T. (2012). Developments in construction-scale additive manufacturing processes. *Automation in Construction*, 21, 262–268

Matt, C, Hess, T, & Benlian, A. (2015). Digital Transformation Strategies. *Business & Information Systems Engineering*: 57(5), 339-343

Mladenovic, S. (2018). Banking in Industry 4.0: Robotic Automation as an Answer to the Challenges of Tomorrow. Retrieved From: https://www.comtradeintegration.com/en/blog/banking-in-industry-4-0-robotic-automation-as-an-answer-to-the-challenges-of-tomorrow/

Ochs, T. & Riemann, U. T. (2018). IT Strategy Follows Digitalisation. Encyclopaedia of Information Science and Technology, Fourth Edition

Oke, A. E., Aghimien, D. O., Aigbavboa, C. O., & Koloko N. (2018). Challenges of Digital Collaboration in The South African Construction Industry. Proceedings of the International Conference on Industrial Engineering and Operations Management Bandung, Indonesia, March 6-8, p. 2472 – 2482

Olawumi, T. O., & Chan, D. W. M. (2018). A Scientometric Review of Global Research on Sustainability and Sustainable Development. *Journal of Cleaner Production*, 183, 231–250

Olawumi, T.O., Chan, D.W.M., & Wong, J.K.W. (2017). Evolution in the Intellectual Structure of BIM Research: A Bibliometric Analysis. *Journal of Civil Engineering and Management*, 23, 1060–1081.

Osunsanmi, T. O., Aigbavboa, C. O. & Oke, A. E. (2018). Construction 4.0: The Future of South Africa Construction Industry. *World Academy of Science, Engineering and Technology International Journal of Civil and Environmental Engineering*, 12, (3), 206-212

Petrillo, A., De Felice, F., Cioffi, R., & Zomparelli, F., (2018). Fourth Industrial Revolution: Current Practices, Challenges, and Opportunities, in Digital Transformation in Smart Manufacturing Digital Transformation in Smart Manufacturing, In Antonella Petrillo, Raffaele Cioffi and Fabio De Felice, Intech. Available from: https://www.intechopen.com/books/digital-transformation-in-smart-manufacturing/fourth-industrial-revolution-current-practices-challenges-and-opportunities

Redmond, A., Hore, A., Alshawi, M. & West, R., (2012). Exploring how information exchanges can be enhanced through Cloud BIM', *Automation in Construction*, 24, 175-183

Reis, J., Amorim, N. & Matos, P. (2018). Transformation: a literature review and guidelines for future in Trends and Advances in Information Systems and Technologies. WorldCIST'18. *Advances in Intelligent Systems and Computing*, 745, 411-421.

Rouse, M. (2017). *Meaning of Digitalisation.* Available on http://whatis.techtarget.com/definition/digitization/

Rüßmann, M., Lorenz, M., Gerbert, P., & Waldner, M. (2015). *Industry 4.0: The Future of*

Productivity and Growth in Manufacturing Industries, Boston Consulting Group, 2015 Report

Sheikhshoaei, F., Naghshineh, N., Alidousti, S., & Nakhoda, M., (2018). Design of a digital library maturity model (DLMM). *The Electronic Library*, 36(4), 607-619

Vaidya, S., Ambad, P., & Bhosle, S. (2018). Industry 4.0: A glimpse. *Procedia manufacturing*, 20(11-12), 233-238.

Valdez-de-Leon, O. (2016). A Digital Maturity Model for Telecommunications Service Providers. *Technology Innovation Management Review*, 6(8), 19-32

Van Eck, N.J., & Waltman, L. (2014). Visualizing bibliometric networks. In Y. Ding, R. Rousseau, & D. Wolfram (Eds.), *Measuring scholarly impact: Methods and practice*, pp. 285–320

Vuksic,V.B., Invansic,L., & Vugec, D.S. (2018). A preliminary literature review on digital transformation case studies. *Conference Proceedings*, Rome Italy Sep 17-18, 2018, 20 (9) Part VIII, 952-957

Webster, J. & Watson, R. (2002). The past to prepare for the future: writing a literature MIS Q., 26(2), 3 - 10

Won, J., Lee, G., Dossick, C. & Messner, J. (2013). Where to focus for successful adoption of Building Information Modeling within organization, *Journal of Construction Engineering and Management* 139(11).

Zeng Y, Wang L, Deng X, Cao X. & Khundker N., (2012). Secure collaboration in global design and supply chain environment: Problem analysis and literature review, *Computers in Industry*, 63, 545-556

Zheng, X., Le, Y., Chan, A.P.C., Hu, Y., & Li, Y., (2016). Review of the application of social network analysis (SNA) in construction project management research. *International Journal of Project Management* 34, 1214–1225

High-Precision Quality Inspection for Screws Using Artificial Intelligence Technology

Qian Huang
Assistant Professor, School of Architecture, Southern Illinois University Carbondale, IL, USA
email: qhuang@siu.edu

Abstract

Bolts, nuts, and screws are widely used in the construction industry, so their quality is critical to the success of a construction project. Inferior blots, nuts, and screws are prone to slippage, cracks or breaks in roofs or walls, and ultimately post life-threatening risks for construction workers and building users. To avoid these dangerous consequences, it is required to carefully inspect and control the quality of each bolt, nut, and screw. Yet, unfortunately, manual inspection conducted by humans is a time-consuming and labor-intensive task, hence, it results in poor detection accuracy and low detection throughput. To address this challenge, in this work, we investigate the use of convolutional neural networks (CNNs) based artificial intelligence to realize high-precision and high-throughput automatic quality inspection. First, we take pictures for 8,200 screw surfaces from a screw manufacturer. After a careful quality examination, each screw picture is marked as "defect-free" or "defective" in a dataset. Then, we explore and propose a low-complexity and low-cost CNN-based neural network architecture. These labeled screw images in the dataset are used to train parameters of the proposed neural network architecture and to verify the resultant detection accuracy. Our experimental results show that the quality detection accuracy reaches 95.13% at steady state, and the detection throughput is 2 or 3 orders of magnitude higher than that of humans.

Keywords: Screw Heads, Defective Inspection, Low Complexity, Convolutional Neural Networks

1. Introduction

Bolts, nuts, and screws are essential elements of construction materials that hold multiple mechanical parts together. As a result, their head defects (*e.g.*, cracks, misalignments, damages) affect the operation and safety of construction projects. Inferior blots, nuts, and screws are prone to slippage, cracks or breaks in roofs or walls, and ultimately post life-threatening risks for construction workers and building users. Hence, it is mandatory to carefully inspect all manufactured bolts, nuts and screws before using them in construction projects (Zawada et al, 2018). Moreover, since a large number of screws can be produced by manufacturing equipment in a short time, we envision that a fast and highly accurate quality inspection method is required. In this way, once defective bolts, nuts, or screws are identified, manufacturers can remove them immediately before packing and shipping them to customers.

With the rapid advancement of computer vision technologies, particularly the emerging artificial intelligence (AI) algorithms (LeCun et al, 2015), machine vision has great potential in inspection, sorting, and quality control of construction materials at the manufacturing stages. Traditionally, manufacturing equipment needs to be frequently stopped and idle for a certain period of time for human-conducted onsite quality inspection. This intermittent manufacturing and inspection manner is inefficient for achieving high-throughput automated production (Martinez et al, 2019). In addition, onsite quality inspection personnel typically need years of working experiences. Furthermore, a human inspector may take tens of seconds or even minutes to complete quality assessment of a screw. In contrast, because AI algorithms have the unique ability to automatically extract and learn intrinsic features from input raw data, the combination of computer vision technologies and AI algorithms is expected to result in low cost, high efficiency, and high throughput quality monitoring and real-time inspection (Ahmed et al, 2012; Fathi et al, 2015). We believe that a screw head image captured by cameras contains a lot of embedded information about its quality degree, which can be automatically and implicitly derived using artificial intelligence algorithms. Therefore, this study plans to investigate and develop effective AI algorithms for rapid and accurate screw quality inspection. The targeted AI algorithm should be user-friendly, reliable, robust, and inexpensive to implement.

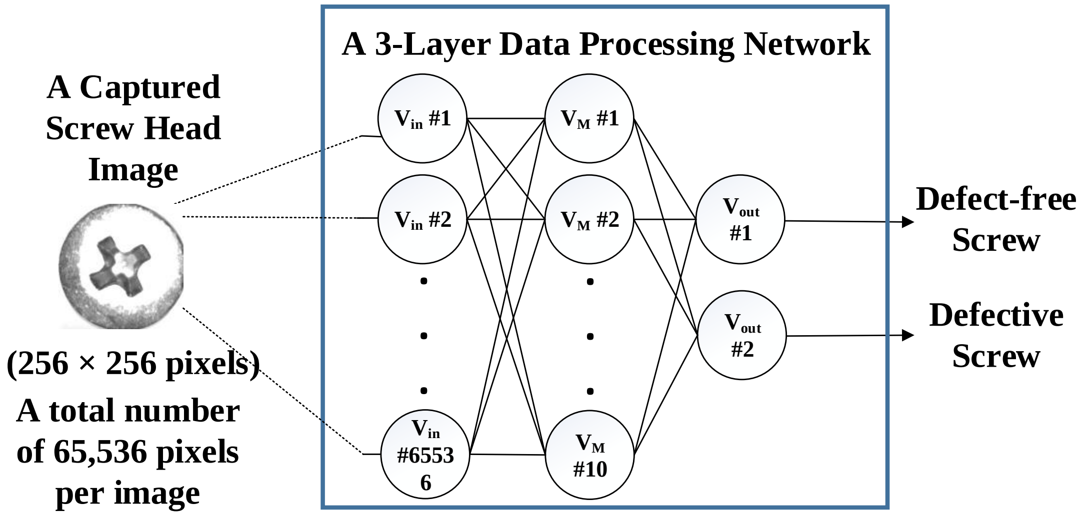


Figure 1: An Example of Using AI Algorithms for Screw Quality Inspection

As illustrated in Figure 1, AI algorithms put a bunch of original data (*i.e.*, each pixel value from a captured screw head image) into a complex data processing network (*e.g.*, a 3-layer fully-connected network), and then check if the output result of this network meets requirements - if yes, the network will be used as the target model; if not, the parameters in the network will be repeatedly updated until the output result meets the requirements. Such data processing networks typically consist of several data processing layers, and the network processing capability increases as the number of layers increase.

In this study, due to the high degree of variability in screw head defects (*e.g.*, cracks, misalignments, damages, broken edges at different locations) as shown in Figure 2, there are no clues about how to effectively extract the intrinsic features of defective screw heads. Hence, it is difficult to manually extrapolate useful features or patterns for quality judgment directly from input screw head images. Note that the image capture position of the screw always changes slightly as the screw moves under the camera. Therefore, as shown in Figure 2, the orientation of screw heads and the appearance of the cross recess are not the same in different images. The detection algorithms to be developed in this study should deal with this orientation variations properly. On the other hand, through literature review, convolutional neural networks (CNN) have demonstrated excellent performance in speech or image recognition/classification, and natural language processing. Although the problems solved in these areas are not the same, these application methods can be summarized as follows: CNNs can automatically learn features from large-scale input raw data and generalize the results to unknown data of the same type. The strong learning ability, fast training speed, and high accuracy of CNNs overcome inherent shortcomings of the traditional neural networks. Therefore, to address this severe challenge of rapid and high-precision inspection of screw quality, we propose to develop appropriate CNN-based AI algorithms. Our proposed CNN-based AI algorithm will create non-linear mappings from a screw head image to a quality decision.

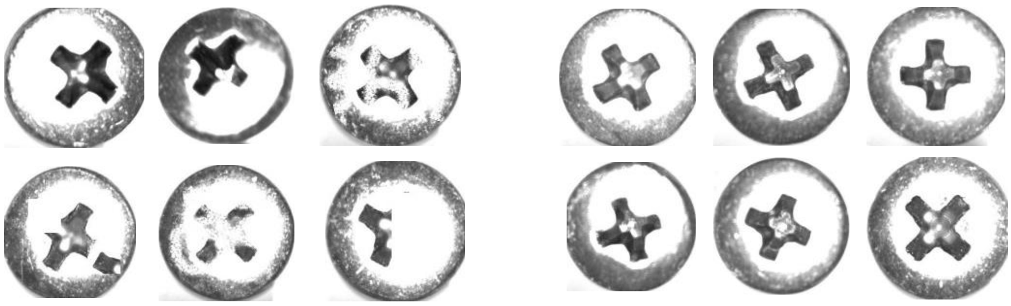


Figure 2: Image Examples of Defective and Defect-free Head Screws

The rest of this paper is organized as follows. Section 2 reviews the literature study related to the use of AI algorithms in object identification or quality inspection. Section 3 describes the proposed low-complexity CNN-based network architecture. Section 4 introduces the experimental test of the proposed CNN architecture using established screw image datasets, and compares this work with existing state-of-the-art designs in the literature. Section 5 concludes this work.

2. Literature Review

In this section, recent research progress and achievements in the area of CNN-based object detection are reviewed and discussed. A variety of CNN architectures have been created for specific applications. For example, the researchers in (Cha et al, 2017) have presented a deep CNN architecture for crack detection in civil infrastructures. Although the reported detection accuracy is very good (about 98%), yet, this CNN architecture is complex, including four convolution layers and two pooling layers. Other CNN architectures for concrete cracks detection is more complex, such as the adoption of 13 convolutional layers in (Silva et al, 2018). The researchers in (Kim et al, 2018) have presented a region-based fully convolutional network for construction object detection. Using the proposed network consisting of 3 convolutional layers, the experimental results have shown a detection accuracy of 96%. The researchers in (Chen et al, 2018) developed deep CNNs to identify defective states of catenary support devices in the electrified railway industry. Even though the experimental measurements show a high detection accuracy and strong robustness in complex outdoor environments, the required CNN architecture is composed of 6 convolutional layers. Later, a deep CNN architecture was developed to detect the defects on metal screw surfaces in (Song et al, 2018). Based on the conventional LeNet-5 (LeCun et al, 1998), this complex CNN architecture utilizes 3 convolutional layers, 3 pooling layers, and 3 fully-connected layers. Furthermore, the input screw image in (Song et al, 2018) is limited to 32×32 pixels. If high-resolution screw images are used as inputs, such as 256×256 pixels or higher, the corresponding CNN architecture will be more complicated.

It can be clearly seen from the above discussion that despite the superior object detection performance, these existing CNN architectures (Cha et al, 2017; Silva et al, 2018; Chen et al, 2018; Song et al, 2018; Kim et al, 2018) rely on complex neural networks, which require a significant amount of computing resources and storage memories to rapidly detect defects. To overcome this resource challenge and still obtain accurate quality assessments, we will explore a low-complexity, resource-efficient CNN architecture, which supports end-to-end computation – from the input screw head images down to an output decision for "defective" or "defect-free". In this sense, our proposed CNN architecture has the potential to accommodate resources of cost-effective hardware platforms, such as a low-cost embedded system consisting of only a microprocessor and limited memory space.

3. Proposed Low-Complexity CNN Architecture

A CNN architecture is composed of various functional layers: convolutional layers, pooling layers, ReLU layers, and fully-connected layers. Convolution is a mathematical operation to simplify data representations by filtering out unwanted noise. As a basic layer of CNNs, a convolutional layer often consists of more than one convolution kernel. Each kernel is convoluted with the input data to form a feature map. Several convolution kernels have been designed to perform image edge detection, sharpening, blurring, etc. Therefore, features (*e.g.*, edges and curves) in images can be extracted through different convolution kernels. The size and number of convolution kernels are pre-defined parameters in CNN architectures. When training a convolutional neural network, the trainable parameters in convolution kernels are automatically adjusted to get better results. This process is called feature learning or feature extraction. In other words, a convolution layer extracts the hidden features from input data and outputs a feature map, which is often with a large dimension. As each convolution kernel can grab the presence of a specific feature, people choose to use multiple kernels to capture different features.

It is well known that a feature map usually has spatial correlation – a pixel is similar to the pixels around it in a large probability. If adjacent pixels are merged, the feature map size will be reduced. Therefore, a pooling layer performs feature selection on the original feature map by taking the maximum or average value to remove redundant features, and reconstructs a new feature map with a small dimension. In average pooling, the average of all values in the pooled area is used as the pooling result. In maximum pooling, the maximum of all values in the pooled area as a pooling result. After pooling operations, the remained information expresses the feature characteristics better. A ReLU (rectified linear unit) layer usually placed after a pooling layer. The goal of the ReLU layer is to introduce nonlinear features into a CNN by forcing its output to zero when the input is negative. To continuously extract deep feature maps, multiple rounds of convolution-pooling-ReLU layers are often created in CNN architectures. As a result, these CNN architectures can compress the height and width of input images, while increasing the number of channels (*i.e.*, depth).

After grabbing enough features of an input image, the final step is how to identify or classify it. The role of a fully-connected layer is to observe the output of previous layer (generally a feature map containing high-level features), and then determine which features are the most relevant to a particular class. A fully connected layer maps the detected features from input images to a separable space, such as a decision of “defective” or “defect-free”.

So far, there is no explicit criteria to guide designers to determine CNN architectures, such as the number of total layers, the number of convolution layers, the size and number of convolution kernels, etc. This is because a neural network is largely dependent on the size, type, hidden features, and complexity of processing tasks. In this work, we figure out how to choose a low-complexity and high-precision CNN architecture through the “trial and error” approach. In this way, an appropriate CNN architecture is proposed in Figure 3, which consists of only 1 convolution layer and 1 pooling layer.

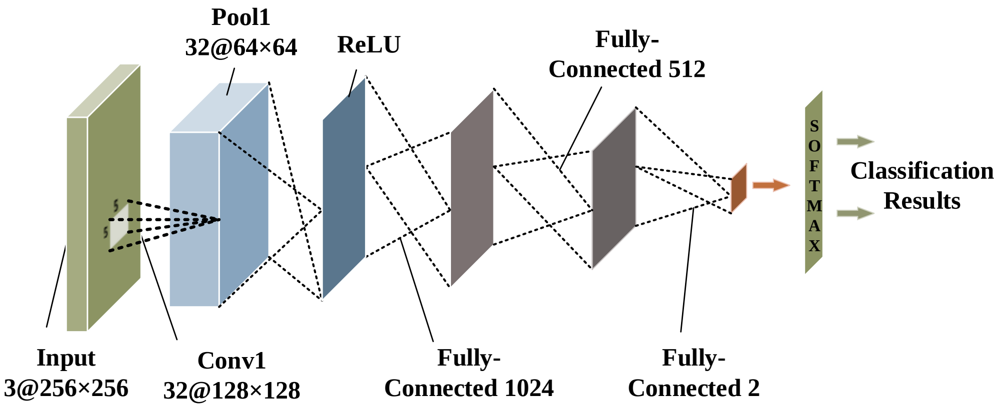


Figure 3: The Proposed Low-Complex CNN Architecture for Screw Quality Classification

As shown in Figure 3, the proposed CNN architecture consists of one input layer, one convolution layer, one pooling layer, one ReLU layer, three fully-connected layers, and a softmax layer. As the resolution of each screw head image is 256×256 pixels with 3 channels (RGB), the input layer has a dimension of 256×256×3. Then, in the convolution layer, 32 convolution kernels with a size of 5×5 are used. The padding option is chosen to be "same", so it makes sure that the output size after convolution is the same as the input size. Hence, the resultant feature map size after convolution is still 256×256×32. After the pooling layer, the size of these feature maps shrinks to 128×128×32. Next, the nonlinearity is added through the ReLU layer, the latest feature maps are passed to the three fully connected layers. Finally, the "defective" or "defect-free" classification decision is provided from the softmax layer. This CNN architecture has been described and implemented in software code using the Python language.

4. Methodology and Design Considerations

Figure 4 illustrates the flowchart of training and validating the proposed CNN architecture. The CNN training is conducted with an established dataset of 8,200 screw images with a dimension of 256×256 pixels. 4,100 screw images are included in a training dataset, while the other 4,100 screw images are included in a test dataset. That means that we use 4,100 training images to train our proposed CNN architecture, and use another 4,100 test images to validate the classification accuracy of the trained CNN architecture. The goal of CNN training is to optimize trainable parameters (weights and biases in each neuron) to maximize the chance of correct defects decision. All trainable parameters are randomly initialized during the training process. Then, the CNN training is based on gradient descent algorithm in the framework of TensorFlow. The gradient descent algorithm consists of two steps. The first step is a feedforward step, which calculates the output value of the CNN for an input image. The second step is a back propagation step, which deviates from the calculated output value of the CNN to modify the network parameters and to slightly improve its performance on an input image. In this manner, all trainable parameters will be updated iteratively.

Learning rate is an important custom parameter that affects the training convergence speed and final classification accuracy of CNNs. For a too high learning rate, the weight update is very large, so CNNs can converge quickly. But it also raises a problem that the weight is not accurate enough to achieve the best solution. Otherwise, for a too small learning rate, CNN training will converge very slowly or even impossible to learn at all. In this study, we carefully tuned the value of learning rate to obtain a good trade-off between the training convergence speed and final classification accuracy. The learning rate for training our proposed CNN architecture was chosen to be 0.001.

Instead of training each input image, multiple input images are entered as a batch (*e.g.*, epoch). The goal is to make the learning process less sharp and the convergence direction more consistent. A large batch size reduces training time and improves stability. However, a large batch size can lead to a decline in model generalization capability. In this study, we chose the epoch size to be 64.

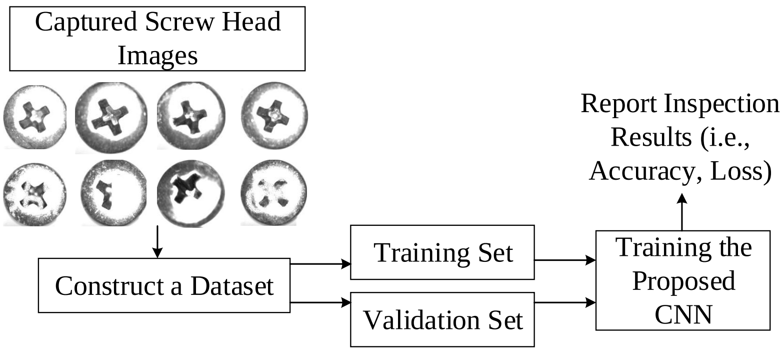


Figure 4: Flowchart of Training and Validating the Proposed CNN Architecture

5. Experimental Results and Discussions

Figure 5 shows how the detection accuracies vary with the number of training epoch. The final training accuracy can be as high as 99.4%, which is much better than conventional methods for screw defect inspection. The final validation accuracy is about 95.13%, which is comparable with the state-of-the-art works in the literature. Figure 6 plots the simulation results for the training and validation losses with respect to the number of training epoch. This figure shows our chosen learning rate is appropriate.

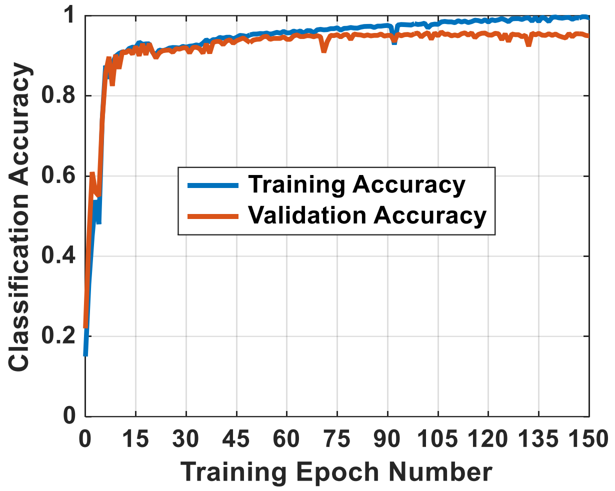


Figure 5: Classification Accuracy vs. Training Epoch Number

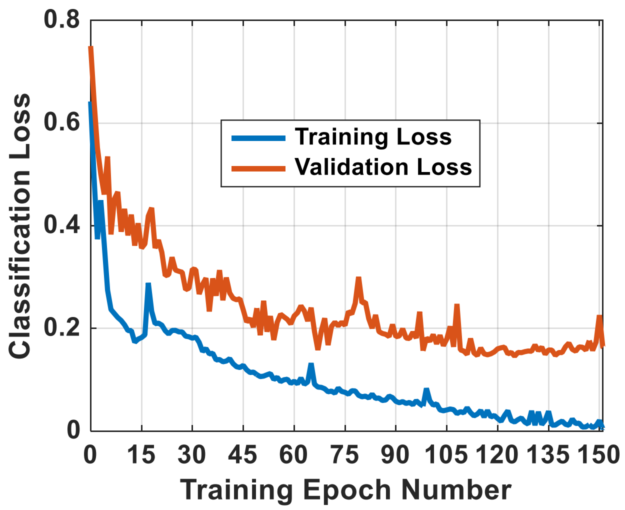


Figure 6: Classification Loss vs. Training Epoch Number

Table 1 summarizes the performance comparison of proposed low-complexity CNN with the state-of-the-art CNN architectures in the literature. Compared with (Cha et al, 2017; Silva et al, 2018; Chen et al, 2018; Song et al, 2018; Kim et al, 2018), the proposed CNN architecture is relatively simple to implement and obtains a comparable classification accuracy. Therefore, our proposed CNN architecture has the potential to be implemented in cost-effective hardware platforms, such as a low-cost embedded system consisting of only a microprocessor and limited memory space. Our proposed AI algorithm spends around 1 second to complete the quality inspection of a screw. Compared with human-conducted quality inspection, our algorithm has 2 or 3 orders of improvement in the detection throughput, hence enabling high-throughput automated production of construction materials.

Table 1: Comparison Summary of this Work with Existing CNN Architectures

	Purpose	CNN Architecture	Classification Accuracy
(Cha et al, 2017)	*crack detection*	*4 convolution layers 2 pooling layers*	*98%*
(Silva et al, 2018)	*concrete crack detection*	*13 convolution layers*	*92.27%*
(Kim et al, 2018)	*construction equipment*	*3 convolution layers*	*96%*
(Song et al, 2018)	*defective metal screw surface*	*3 convolution layers 3 pooling layers*	*98%*
(Chen et al, 2018)	*Defective fastener detection*	*6 convolution layers*	*92.78%*
This work	*defective screw head*	*1 convolution layer 1 pooling layer*	*95.13%*

6. Conclusions

In order to achieve rapid, high-throughput, and high-precision screw head quality inspection, a vision-based artificial intelligence algorithm is investigated in this work. The proposed convolutional neural network (CNN) architecture consists of only one convolution layer and one pooling layer, so it is a low-complexity network architecture with an acceptable high accuracy of 95.13%. This study has the great potential to replace human-conducted onsite inspections to realize high-throughput automated production of construction materials.

7. Limitations and Future Work

Despite the very high detection accuracy, this AI architecture is very complex. Thus, it is a challenge to implement our proposed AI algorithm is resource-limited computational platforms, such as an embedded system which is connected with a camera that captures raw screw head images. A typical embedded system consists of only a quad-core microprocessor and limited memory size. To solve this problem, I will investigate low-complexity, energy-efficient AI algorithm implementation, and adopt it to a typical hardware platform (*e.g.*, Raspberry PI) to achieve fast end-to-end quality inspection.

Acknowledgements

The authors would like to acknowledge the support by the 2019 CASA summer research grant of Southern Illinois University Carbondale.

References

Ahmed, M., Haas, C., & Haas, R. (2012). Using digital photogrammetry for pipe-works progress tracking. *Canadian Journal of Civil Engineering*, 39(9), 1062-1071.

Cha, Y., Choi, W., & Buyukozturk, O. (2017). Deep learning-based crack damage detection using convolutional neural networks. *Journal of Computer-Aided Civil and Infrastructure Engineering*, 32(5), 361-378.

Chen, J., Liu, Z., Wang, H., Nunez, A., & Han, Z. (2018). Automatic defect detection of fasteners on the catenary support device using deep convolutional neural network. *IEEE Transactions on Instrumentation and Measurements*, 67(2), 257-269.

Fathi, H., Dai, F., & Lourakis, M. (2015). Automated as-built 3D reconstruction of civil infrastructure using computer vision: achievements, opportunities, and challenges. *Advanced Engineering Informatics*, 29(2), 149-161.

Kim, H., Kim, H., Hong, Y., & Byun, H. (2018). Detecting construction equipment using a region-based fully convolutional network and transfer learning. *ASCE Journal of Computing in Civil Engineering*, 32(2), 04017082.

Lecun, Y., Bottou, L., Bengio, Y., & Haffner, P. (1998). Gradient-based learning applied to document recognition. *Proceedings of the IEEE*, 86, 2278 – 2324.

LeCun, Y., Bengio, Y., & Hinton, G. (2015). Deep learning. *Nature*, 521(7553), 436-444.

Martinez, P., Ahamd, R., & Hussein, M. (2019). A Vision-based system for pre-inspection of steel frame manufacturing. *Automation in Construction*, 97, 151-163.

Silva, W., & Lucena, D. (2018). Concrete cracks detection based on deep learning image classification. *Proceedings*, 2(8), 489.

Song, L., Li, X., Yang, Y., Zhu, X., Guo, Q., & Yang, H. (2018). Detection of micro-defects on metal screw surfaces based on deep convolutional neural networks. *Sensors*, 18, 3709.

TensorFlow, https://www.tensorflow.org/

Zawada, A., & Wierucka, I. (2018). A case study in technological quality assurance of a metric screw thread. *Measurement*, 114, 208-217.

Improving Prediction Accuracy of Machine Learning Energy Prediction Models

Manav Mahan Singh[1*], Sundaravelpandian Singaravel[1] and Philipp Geyer[1]
[1]Architectural Engineering Division, Department of Architecture, KU Leuven
* email: manavmahan.singh@kuleuven.be

Abstract

Machine learning (ML) energy prediction models are useful to estimate the building energy demand with short response time, particularly important for developing energy-efficient building designs at an early stage of design. Component-based machine learning model (CBML) is the state-of-the-art development of ML energy prediction and useful to improve the generalizability of models. The concept of CBML is based on decomposing the design artefact in an engineering-related way and calculating intermediate parameters such as heat flows through building elements, followed by energy component at zone level and finally total energy demand at building level. Previous research showed that the method works but the improvement of the range of design and accuracy are still desirable to make the method more aligned to architectural design. Therefore, in this paper, we propose to enrich the training data with new building shapes and enhanced features typical for architectural design. For training each model of CBML, the data is collected by performing parametric energy simulations with three different building shapes and tested on fourth shape. A manual feature engineering approach is carried out by extracting useful features which have an influence on the target value. The accuracy of CBML is ascertained by *coefficient-of-determination* (*R^2-values*) and *mean absolute percentage error (MAPE)*. The effect of enriching data with different building shape is studied by training ML model while increasing data sequentially and recording the improvements in the prediction accuracy. To study the effect of enhancing feature, CBML is developed with two types of features – raw and enhanced features and recording the change in the prediction accuracy. Furthermore, the influence of features is calculated using permutation importance to study the effect of additional features. The accuracy of total building energy model on new building shape improves from 5.18% to 3.14% *(MAPE)* and 0.9970 to 0.9988 *(R^2)* after enriching the data with several building shapes and enhancing the features.

Keywords: Feature Engineering, Training Data, Feature Importance, Performance, Permutation Importance.

1. Introduction

Machine learning (ML) energy prediction models are useful to predict the building's energy demand in a short response time compare to traditional energy simulation tool (Geyer & Singaravel, 2018; Singaravel, Geyer, & Suykens, 2018). This is quite relevant for predicting energy demand and developing energy-efficient building designs at an early stage of design when the design parameters are inherently uncertain (Struck, de Wilde, Hopfe, & Hensen, 2009; Tian et al., 2018; Van Gelder, Janssen, & Roels, 2014). The concept of component-based machine learning model (CBML) is introduced by Geyer and Singaravel to improve the ML model generalization to design cases not present within training design cases (Geyer & Singaravel, 2018). In monolithic models, target variable is directly predicted using building design parameters as input features. However, the concept of CBML is based on decomposing the design artefact in an engineering-related way and calculating intermediate parameters. CBML offers a unique opportunity to integrate an energy prediction model easily with multi-level-of-detail (multi-LOD) building information model (BIM) data structure (Abualdenien & Borrmann, 2018; Geyer, Singh, & Singaravel, 2018). The integration of CBML with BIM models has the potential to streamline the design and energy prediction process at any stage of the design process (Singh, Singaravel, & Geyer, 2018).

In previous implementations of the CBML, a decrease of the accuracy is observed when using component models trained on parametric simulation results from rectangular buildings on more complex building shapes (Geyer & Singaravel, 2018). Reason being complex environmental interactions present for complex building shapes were not present within the training space characterized by rectangular buildings. In this research work, the accuracy of CBML is improved by enriching the training data with several building shapes and enhancing features. It has been proven that the accuracy of ML models increases with the training data irrespective of the algorithm in speech learning application (Banko & Brill, 2001). The approach of enhancing features to improve model accuracy is discussed in few studies (Catalina, Virgone, & Blanco, 2008; Cheng & Cao, 2014). The accuracy of the model improves with newly developed features, but it lacks the use of formal techniques to study the feature importance. The objectives of this study are:

1) To study the effect of enriching data with several building shapes to improve the prediction accuracy of ML models.
2) To study the effect of enhancing features on the prediction accuracy of ML models.

2. Literature Review

There are several efforts made to make quick energy prediction using engineering-surrogate or data-driven models (Van Gelder, Das, Janssen, & Roels, 2014). These models offer few advantages over traditional energy simulation tools in terms of computational time at the cost of prediction accuracy. It is possible to evaluate a large number of simulation model using these approaches which are required for making probabilistic energy prediction at the early stage of design (Van Gelder, Janssen, et al., 2014). There are several research studies published on the use of machine learning models for energy prediction (Fumo, 2014). However, these models offer limited integration with the design process and the applicability of the models is limited to the training design case. The concept of CBML is introduced to overcome multiple limitations of monolithic ML energy prediction models such as extensionality to new design cases, training models for generic building elements, and integration with BIM model (Geyer & Singaravel, 2018).

In other machine learning applications such as speech recognition, it has been proven that enriching training data with the new cases improves the prediction accuracy of the models (Banko & Brill, 2001; Halevy, Norvig, & Pereira, 2009). Van Gelder, Das, et al., 2014 studies the effect of increasing the number of samples on the prediction accuracy, but the effect of enriching training data with various building shapes is not tested on the energy prediction models. There are few studies which utilize data from various building shapes for the training of energy prediction models, but the prediction accuracy is never tested on the building shape outside of the training data (Asadi, Amiri, & Mottahedi, 2014; Catalina et al., 2008). A manual feature engineering approach was carried out by using domain knowledge and extracting useful features which have an influence on the target value (Catalina et al., 2008). Previously developed machine learning energy prediction approaches document limited applicability of the models on new design cases or the accuracy of the models reduces.

3. Structure of CBML and training of ML model

The concept of CBML is based on decomposing the design artefact in an engineering-related way and calculating intermediate parameters. In the presented approach the building is composed of a zone which has building elements such as walls, windows, floors and roofs. Figure 1 shows the CBML architecture utilized in this paper. ML models at building elements like walls first predict heat flows through them. Information on heat flows together with design information like area are utilized by ML models at zone level to make predictions on zone energy demand. Finally, ML model at building level utilizes information of zone energy demand together with HVAC design information to make the final energy prediction. Five types of building elements are considered in this model, namely, *Wall, Window, Ground Floor (GFLoor), Intermediate Floor (IFloor)* and *Roof*. The heat flows through the building components are summed up as *Total Heat Flows* and provided as input for zone level models i.e. *Heating Energy, Cooling Energy, Lighting Energy* and *Equipment Energy*. The zone level outputs are used to train the *Building Total Energy* model. The complete list of features used for training of each model of CBML is available *Table 2*.

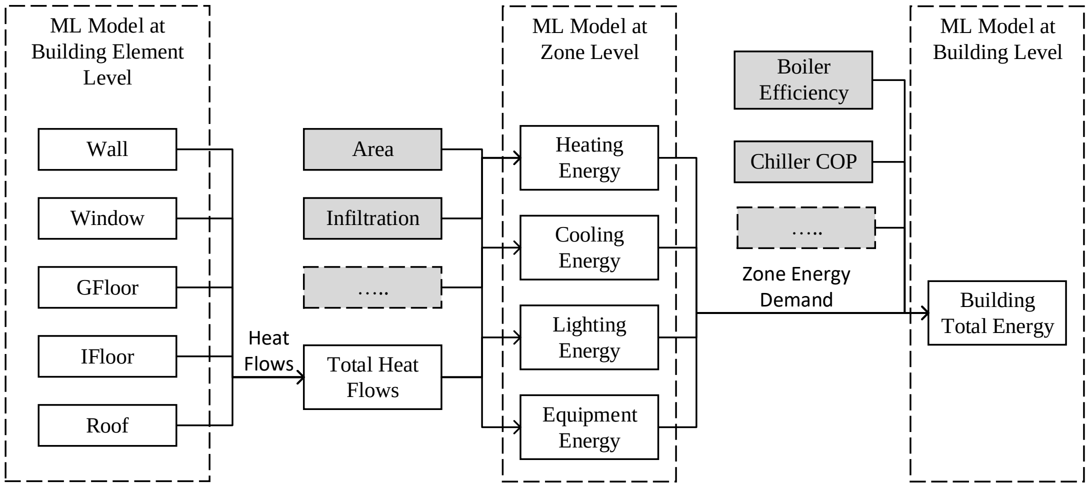


Figure 1. Structure of component-based machine learning model

The models have two hidden layers with a specified number of neurons. There are three hyper-parameters which are the number of neurons in first and second hidden layer (NN1 and NN2) and L2-regularisation which are tuned to obtain a suitable model. L2-regularisation is used to avoid overfitting issue by adding a squared magnitude of coefficients as penalty term to the loss function (Ng, 2004). The few combinations of hidden layers NN1 {10, 20}, NN2 {4, 8} and L2-regularisation {0.001, 0.0001, 0.00001} are tested to identify a good combination of hyper-parameters for each model. These hyper-parameters are tuned each time using the validation data which is 20% of training data. The performance of each model of CBML is estimated by two parameters which are coefficient of determination (R^2) and mean absolute percentage error (MAPE). R^2 represents a measure of second order and it is more sensitive to mid-range values while MAPE is a measure of the first order and more suitable to low-range values (Géron, 2017). Thus, both parameters are important to assess the model accuracy. ML models are developed using Keras and TensorFlow as a backend (Chollet, 2015).

4. Research methodology

This section consists of three sub-sections. The section 4.1 details out the data collection process which is used to train ML models. The section 4.2 explains the method for studying the effect of enriching the training data. The section 4.3 elaborates the details the method to study the effect of enhancing features.

4.1 Data collection for training ML models

We have collected data using parametric simulation with four different building shapes, shown in *Figure 2*. These are commonly used building shapes in office design and represents architectural variations at an early stage of design. The first three shapes rectangular (*Shape1*), plus (*Shape2*) and L-shaped (*Shape3*) building are used for training CBML and the performance of the model is tested on H-shaped (*Shape4*) building. There are three options for the number of floors i.e. one floor, two floors and three floors and 2000 training instances for each of these options. Thus, there a is total of 18000 training instances, 6000 for each shape. *Shape4* mentioned under test data set is explicitly used for estimating and reporting the accuracy of developed ML models. The detail of design parameters and their ranges are mentioned in *Table 1*. We used Sobol sequence to generate a random combination of design parameters considering uniform distribution in the specified range (Herman & Usher, 2017).

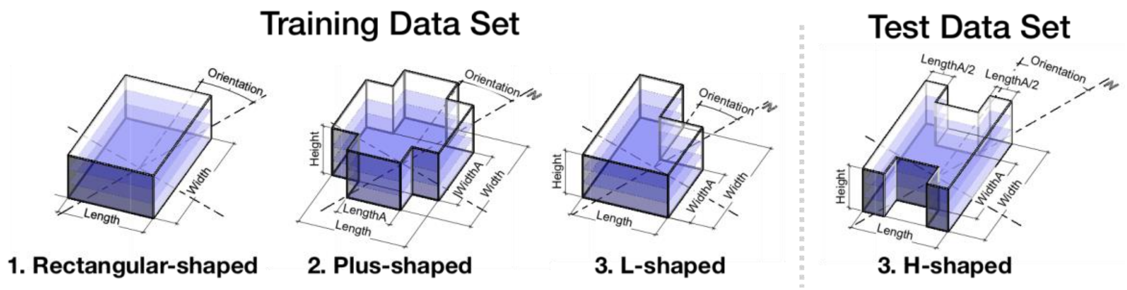


Figure 2. Architectural designs studied in this paper

Table 1. Detail of parameters with the ranges

Parameter	Unit	Range
Length	(meters)	10, 100
Width	(meters)	10, 100
Height	(meters)	3, 5
Orientation	Degrees	0, 180
Infiltration	(ACH)	0.2, 1
U_Wall	(W/m^2°K)	0.1, 0.75
U_GFloor	(W/m^2°K)	0.1, 0.75
U_Roof	(W/m^2°K)	0.1, 0.5
U_IFloor	(W/m^2°K)	0.1, 0.75
HC_Slab	(J/m^3°K)	800, 1600
U_Window	(W/m^2°K)	0.25, 1.5
g_Window	-	0.1, 0.9
WWR_N/E/W/S*	-	0.01, 0.95
Operating Hours	(hours)	8, 10
Lighting Heat Gain	W/m^2	5, 15
Equipment Heat Gain	W/m^2	10, 15
Chiller COP	-	3, 5
Boiler Efficiency	-	0.7, 0.9

A parametric simulation model has been set up with dynamic energy simulation tool EnergyPlus to generate data for training ML models. We have used weather data of Munich which represents most part of western Europe. The use of the building is office which follows a typical 5-days schedule. The parameters *U_Wall*, *U_GFloor*, *U_Roof*, *U_IFloor*, and *U_Window* imply u-value for walls, ground floor, roof, intermediate floors and windows respectively. *g_Window* implies g-value for windows and *HC_Slab* is heat capacity for floor slabs. *WWR_N/E/W/S* stands for window-to-wall ratio in north, east, west and south directions respectively and chiller COP is the coefficient of performance for chiller. The heating and cooling setpoints are 20 and 24°C and setback points are 10 and 28°C respectively. The energy model considers the effect of daylight in the zone and reduces the amount of artificial light to achieve lux level of 500. The occupant load is one person per 10 m^2. The simulation model is based one-zone-per-floor rule i.e. assuming one zone is present at each level.

The energy simulation is performed at the Vlaams Super Computer (VSC) using ten nodes equivalent to 360 cores at a clock speed of 2.3GHz.

4.2 Effect of enriching training data

Each ML model of CBML are trained using the first shape from training data i.e. rectangular building shape and the performance of ML models is used as a base case. To see the effect of increasing data, each model of CBML is trained again with additional shape one-by-one. Thus, recording the accuracy of each model of CBML with increasing data step-by-step will show the effect of enriching training data. To see the effect of training data, raw features listed in *Table 2* are used.

4.3 Effect of enhancing features

We are using two types of features: (1) *Raw Features* and (2) *Enhanced Features*. *Raw Features* are the features easily available for each component in digital models and mostly represents geometric and thermo-physical properties of the element. As listed in *Table 2*, *Raw Features* for building element level models are area and thermal heat transfer coefficients (u-value). *Raw Features* for zone level models represent size (floor area and height), heat flows, infiltration and internal heat gains. *Enhanced Features* for building element level model are *Raw Features* and additional features. For example, heat flow through wall component depends on the area, orientation and u-value. Additionally, radiation and the zone which is it associated must be represented in the features to predict heat flows. The zone is represented by *Zone Features* i.e. *Zone Area, Zone Volume, Total Light Heat Gain, Total Equipment Heat Gain, Total Infiltration, Operating Hours, Heat Capacity, Solar Radiation, Wall Area × U_Wall, GFloor Area × U_GFloor, Roof Area × U_Roof, Window Area × U_Window, IFloor Area × U_IFloor*. *Zone Features* and *Total Heat Flows* are used as input for *Zone Heating* and *Cooling Energy* model. Zone area, lighting or equipment heat gain and operating hours are used as a feature for lighting and equipment energy models. For *Building Total Energy*, both features represent the size of the building, system efficiency and energy outputs from zone level models.

Table 2. Details of features used in training each model of CBML

	ML Model	**Raw Features**	**Enhanced Features**
Building element level	**Wall**	area, orientation, u-value	area, orientation, u-value, radiation, zone features
	Window	area, orientation, u-value, g-value	area, orientation, u-value, g-value, radiation, zone features
	GFloor	area, u-value	area, u-value, zone features
	Roof	area, u-value	area, u-value, radiation, zone features
	IFloor	area, u-value	area, u-value, zone features, adjacent zone features
Zone level	**Heating energy**	area, height, light heat gain, equipment heat gain, infiltration, operating hours, heat capacity, total heat flows	zone features, total heat flows
	Cooling energy		
	Lighting energy	area, light heat gain, operating hours	area, total light heat gain, operating hours
	Equipment energy	area, equipment heat gain, operating hours	area, total equipment heat gain, operating hours
Building level	**Total energy**	total floor area, total volume, boiler efficiency, chiller COP, lighting energy, equipment energy, heating energy, cooling energy	total floor area, total volume, boiler efficiency, chiller COP, lighting energy, equipment energy, heating energy, cooling energy

We are using deep learning neural network architecture for training ML models which is a black-box estimator. To understand the importance of features in such ML model, we used permutation importance technique described in Breiman, 2001 and implemented using python library developed by Korobov & Lopuhin, 2016. The calculation of feature importance using the permutation importance technique is an iterative process. We have used 25 iterations to get reliable results. This step will give the feature importance of each feature in ML models and thus useful to know how enhancing the feature can be useful for further development.

5. Results

In this section, the prediction accuracy of CBML is documented to observe the effect of enhancing training data and features. The effect of enhancing training data is presented in section 4.1 and the effect of enhancing features is presented in section 4.2.

5.1 Effect of increasing training data

CBML is initially trained using the simulation data from *Shape1* (rectangular-shaped building). In the next step, the training data is enriched with the simulation data from *Shape2* (plus-shaped building) and finally, the simulation data from *Shape3* (L-shaped building) is also used for the training of ML models. The performance of each ML model of CBML, recorded in terms of R^2 and MAPE, is presented in *Figure 3*. *Total Heat Flows* is the sum of heat flows through the building components for a zone. The point (+) represents the performance of the ML model, the solid line represents the trends in the performance with respect to the number of shapes and the dash-dot line represents the linear-fit of the trend line. The performance of *Window* and *IFloor Heat Flow* models is not plotted in this figure as it will not fit in the scale. *Table 3* should be referred for the prediction accuracy of these component models. In most of ML models, the accuracy increases with the increase in training data, but it is not always the same. There is not much improvement in R^2 values for zone level or building level models as the values are quite high with *Shape1* also. But the MAPE improves for these models with the increase in the data, showing improvement in low-range values.

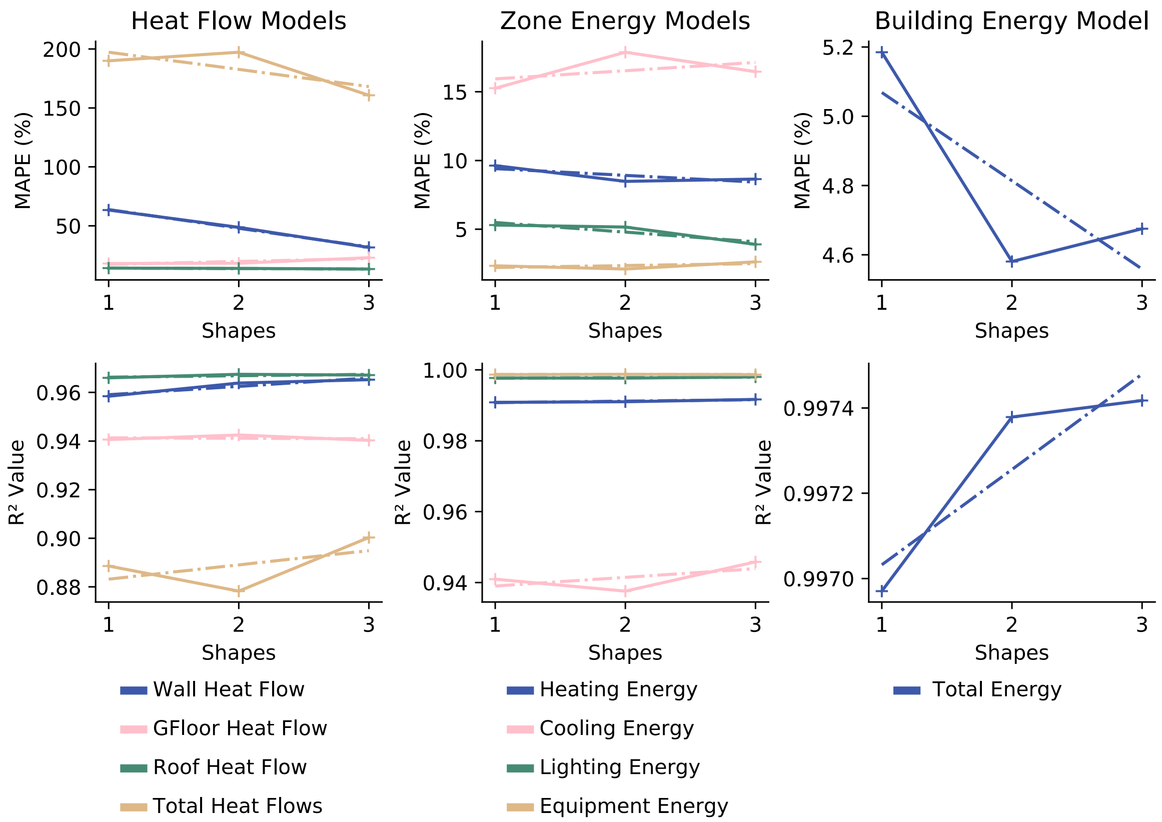


Figure 3. Effect of increasing training data on the prediction performance of ML models

5.2 Effect of enhancing features

Each model of CBML is trained using two types of features – raw and enhanced features as mentioned in *Table 2*. The performance of each ML model is recorded in terms of MAPE and R^2 and presented in

Table 3. It has three training scenarios of CBML. First, *Raw Features (Shape1)*, which means the training data is used from *Shape1* using *Raw Features*. Second, *Raw Features (Shape1-3)* means the training data is used from *Shape1*, *Shape2* and *Shape3* using *Raw Features* again. Third, *Enhanced Features (Shape1-3)* implies the same training data as the previous step but with *Enhanced Features*. It should be noted that there is a significant improvement in MAPE for each ML model. The accuracy of *IFloor* and *Window Heat Flow* model improves with the use of enhanced features. The accuracy of zone level models improves much more with the use of enhanced features compare the increasing in the training data. There is a similar improvement in the building energy model after increasing the training data or enhancing the features.

Table 3. Effect of training data and features on prediction accuracy of CBML

Feature and Shapes	**Raw Features (Shape1)**		**Raw Features (Shape1-3)**		**Enhanced Features (Shape1-3)**	
Model	**MAPE (%)**	**R2**	**MAPE (%)**	**R2**	**MAPE (%)**	**R2**
Wall Heat Flow	63.41	0.9584	31.68	0.9652	22.97	0.9889
Window Heat Flow	18.05	0.9406	814.03	0.9745	328.61	0.9922
GFloor Heat Flow	14.09	0.9660	22.96	0.9403	8.95	0.9882
Roof Heat Flow	18.67	0.9649	13.30	0.9671	7.70	0.9888
IFloor Heat Flow	340.46	0.0145	349.16	0.0143	71.24	0.9885
Total Heat Flows	189.97	0.8886	160.82	0.9003	91.73	0.9863
Zone Heating Energy	9.623	0.9908	8.64	0.9917	4.18	0.9981
Zone Cooling Energy	15.26	0.9410	16.46	0.9459	7.75	0.9838
Zone Lighting Energy	5.30	0.9977	3.90	0.9980	4.60	0.9978
Zone Equipment Energy	2.33	0.9987	2.62	0.9986	1.69	0.9989
Building Total Energy	5.18	0.9970	4.68	0.9974	3.14	0.9988

The feature importance is calculated for the last model only i.e. *Total Energy Model* trained using *Shape1-3* and *Enhanced Features*. The results for each model are presented as bar graphs in *Figure 4***Error! Reference source not found.**. The *Zone Features* consists of several features representing the characteristics of zone. Hence the feature importance of *Zone Features* is sum of the feature importance of these features. For *Wall* and *Window* heat flow, the area is the most important feature. For *Roof* and *GFloor*, *Zone Features* is the most important feature, which means there is some feature in *Zone Features* which characterizes the heat flow through these components more appropriately. For *IFloor, Zone Features* and *Adjacent Zone Features* shows similar importance. For *Zone Heating Energy* model, *Zone Features* are quite important compared to *Total Heat Flows* which represents heat flow through the building elements. For *Zone Cooling Energy* model, both *Total Heat Flows* and *Zone Features* are important. For *Zone Lighting* and *Equipment Energy* models, the results are self-explanatory. For *Building Total Energy* model, *Heating Energy* has the highest influence, followed by *Equipment Energy*, *Lighting Energy*, *Total Floor Area* and *Boiler Efficiency*.

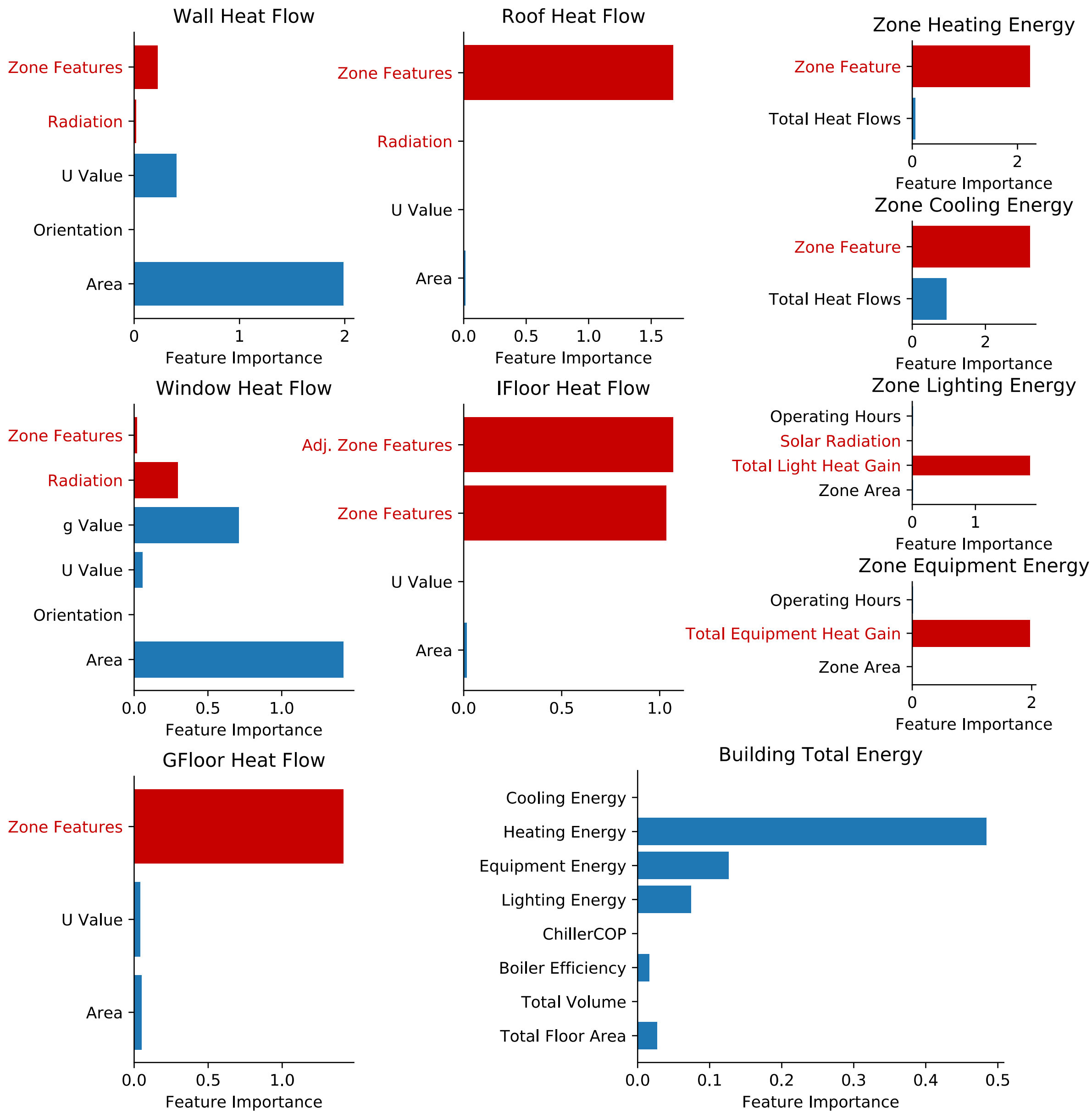


Figure 4. Feature importance for each model (enhanced features are marked with red colour)

6. Discussion

The section discusses the applicability and limitations of trained ML models in the wider context. CBML offers more generalizable structure to perform energy prediction for the building shapes of architectural complexity. The developed ML models are performing with good accuracy on the design case outside of the training data set from the perspective of the whole building with its specific architectural shape. The advantage of components is that their usage stays within the training range. As a consequence, these models are useful for the energy prediction of building shapes which are not included in the training case.

It is expected that the prediction accuracy of the ML model will improve with as the training data increases, but not always. *Building Total Energy* model is performing better when the training data of *Shape1* is enriched with the data of *Shape2*, but there is no improvement when it is enriched further with the data of *Shape3*. Also, there is not much improvement in R^2 for total energy model which is close to 0.999 in the first instance itself. It means that the data enrichment is useful to improve the accuracy for low range values. The building element level models always show improvement after data enrichment. For zone level models, sometimes it performs better and sometimes there is no improvement. There is further investigation required to when enriching data with a new shape will be useful.

The feature enhancement improves the prediction accuracy of each ML model of CBML. It will be useful to know which feature influences the accuracy of the ML model as adding all the features may not be useful. Furthermore, it provides useful information for the selection of features. It is evident from *Figure 3* that the inaccuracies in ML models at building element level may or may not result in the inaccuracies in zone level models. It depends on the importance of heat flows in the zone level models. The feature importance for zone level models reveals that the heat flows only influence the *Zone Cooling Energy Model* a little and has no almost influence on the *Zone Heating Energy Model*. Also, *Total Energy* model at the building level, *Heating Energy* has the highest influence which is not influenced by *Total Heat Flows*. Thus, the inaccuracies in building element level model result in less inaccuracies in zone level models or building level model.

The training of CBML is performed using the data generated using dynamic energy simulation tool. The data generation process is simplified following certain assumptions such as *one-zone-per-floor model*, no presence of urban context and use of building as office etc. Thus, the CBML is valid for the assumptions which are used to perform dynamic energy simulation of buildings. Also, it utilizes weather data for Munich. However, a similar approach can be adopted after generating data with other assumptions and location.

7. Conclusions

The component-based machine learning model is useful for extending the ML model developed with some building shapes on the building shapes outside of the training data. The study shows that the prediction accuracy of the model improves with the inclusion of more building shapes in the training data in general. Also, it has been shown that CBML can be used to make the energy prediction of a building shape which is not included in the training data. The accuracy of total energy model at building level improves from 5.18% to 4.68 % *(MAPE)* and 0.9970 to 0.9974 *(R^2)* after enriching the training data with *Shape2* and *Shape3*. However, it is complex to understand which building shapes should be used for data enrichment.

The prediction accuracy of each model in CBML improves after enhancing the features. The feature importance exercise confirms that the additional features influence the prediction accuracy of ML models. For building element level models, *Zone Features* are really important as after improvement, the accuracy of models improve significantly evident with the reduction in MAPE and increase in R^2 values. The similar trend follows for zone level models as both performance measures improve after enhancing the features. This is evident in the feature importance graph also where the additional features show good importance in the zone level models. We didn't enhance the features for total energy model at the building level, but more accurate prediction at building element level and zone level models improves its prediction accuracy. The accuracy of total energy model at building level improves from 4.68% to 3.14 % *(MAPE)* and 0.9974 to 0.9988 *(R^2)* after enhancing the features. But the features should be selected more carefully for the development of each model of CBML as all the additional features may not be important to improve the prediction accuracy. Thus, the feature enhancement should be supplemented with the calculation of feature importance for each model. It is useful for the identification of relevant features for each model. The overall accuracy of *Total Energy* model at building level improves from 5.18% to 3.14% *(MAPE)* and 0.9970 to 0.9988 *(R^2)* after enriching training data and enhancing the features.

Acknowledgement

The authors want to acknowledge the support of Deutsche Forschungsgemeinschaft (DFG) for funding the research through research unit FOR 2363. The computational resources and services used in this work were provided by the VSC (Flemish Supercomputer Center), funded by the Research Foundation - Flanders (FWO) and the Flemish Government – department EWI.

References

Abualdenien, J., & Borrmann, A. (2018). Multi-LOD model for describing uncertainty and checking requirements in different design stages. In *Proceedings of the 12th European Conference on Product and Process Modeling*. Copenhagen, Denmark.

Asadi, S., Amiri, S. S., & Mottahedi, M. (2014). On the development of multi-linear regression analysis to assess energy consumption in the early stages of building design. *Energy and Buildings*, *85*, 246–255. https://doi.org/10.1016/j.enbuild.2014.07.096

Banko, M., & Brill, E. (2001). Scaling to Very Very Large Corpora for Natural Language Disambiguation. In *Proceedings of the 39th Annual Meeting on Association for Computational Linguistics* (pp. 26–33). Stroudsburg, PA, USA: Association for Computational Linguistics. https://doi.org/10.3115/1073012.1073017

Breiman, L. (2001). Random Forests. *Machine Learning*, *45*(1), 5–32. https://doi.org/10.1023/A:1010933404324

Catalina, T., Virgone, J., & Blanco, E. (2008). Development and validation of regression models to predict monthly heating demand for residential buildings. *Energy and Buildings*, *40*(10), 1825–1832. https://doi.org/10.1016/j.enbuild.2008.04.001

Cheng, M.-Y., & Cao, M.-T. (2014). Accurately predicting building energy performance using evolutionary multivariate adaptive regression splines. *Applied Soft Computing*, *22*, 178–188. https://doi.org/10.1016/j.asoc.2014.05.015

Chollet, F. (2015). Keras. Retrieved May 6, 2019, from https://keras.io

Fumo, N. (2014). A review on the basics of building energy estimation. *Renewable and Sustainable Energy Reviews*, *31*, 53–60. https://doi.org/10.1016/j.rser.2013.11.040

Géron, A. (2017). *Hands-On Machine Learning with Scikit-Learn and TensorFlow: Concepts, Tools, and Techniques to Build Intelligent Systems*. (N. Tache, Ed.) (Ninth). Sebastopol, CA: O'Reilly Media, Inc. Retrieved from https://www.oreilly.com/library/view/hands-on-machine-learning/9781491962282/

Geyer, P., & Singaravel, S. (2018). Component-based machine learning for performance prediction in building design. *Applied Energy*, *228*, 1439–1453. https://doi.org/10.1016/j.apenergy.2018.07.011

Geyer, P., Singh, M. M., & Singaravel, S. (2018). Component-Based Machine Learning for Energy Performance Prediction by MultiLOD Models in the Early Phases of Building Design. In *Advanced Computing Strategies for Engineering* (pp. 516–534). https://doi.org/10.1007/978-3-319-91635-4_27

Halevy, A., Norvig, P., & Pereira, F. (2009). *The Unreasonable Effectiveness of Data*. *Intelligent Systems, IEEE* (Vol. 24). https://doi.org/10.1109/MIS.2009.36

Herman, J., & Usher, W. (2017). SALib: An open-source Python library for Sensitivity Analysis. *The Journal of Open Source Software*, *2*(9), 97. https://doi.org/10.21105/joss.00097

Korobov, M., & Lopuhin, K. (2016). Inspecting Black-Box Estimators. Retrieved April 10, 2019, from https://eli5.readthedocs.io/en/latest/blackbox/index.html

Ng, A. Y. (2004). Feature selection, L 1 vs. L 2 regularization, and rotational invariance. In *Twenty-first international conference on Machine learning - ICML '04* (p. 78). New York, New York, USA: ACM Press. https://doi.org/10.1145/1015330.1015435

Singaravel, S., Geyer, P., & Suykens, J. (2018). Deep Learning Neural Networks Architectures and Methods: Building Design Energy Prediction by Component-Based Models. *Advanced Engineering Informatics*, submitted.

Singh, M. M., Singaravel, S., & Geyer, P. (2018). Information Exchange Scenarios between Machine Learning Energy Prediction Model and BIM at Early Stage of Design. In R. Caspeele, L. Taerwe, & D. M. Frangopol (Eds.), *Publications of the Sixth International Symposium on Life-Cycle Engineering* (pp. 487–494). Ghent, Belgium: CRC Press.

Struck, C., de Wilde, P. J. C. J., Hopfe, C. J., & Hensen, J. L. M. (2009). An investigation of the option space in conceptual building design for advanced building simulation. *Advanced Engineering Informatics*, *23*(4), 386–395. https://doi.org/10.1016/j.aei.2009.06.004

Tian, W., Heo, Y., de Wilde, P., Li, Z., Yan, D., Park, C. S., … Augenbroe, G. (2018). A review of uncertainty analysis in building energy assessment. *Renewable and Sustainable Energy Reviews*, *93*, 285–301. https://doi.org/10.1016/j.rser.2018.05.029

Van Gelder, L., Das, P., Janssen, H., & Roels, S. (2014). Comparative study of metamodelling techniques in building energy simulation: Guidelines for practitioners. *Simulation Modelling Practice and Theory*, *49*, 245–257. https://doi.org/10.1016/j.simpat.2014.10.004

Van Gelder, L., Janssen, H., & Roels, S. (2014). Probabilistic design and analysis of building performances: Methodology and application example. *Energy and Buildings*, *79*, 202–211. https://doi.org/10.1016/j.enbuild.2014.04.042

Towards a Decentralised Common Data Environment using Linked Building Data and the Solid Ecosystem

Jeroen Werbrouck[1,*], Pieter Pauwels[2], Ghent University[2], Jakob Beetz[2], Léon van Berlo[3],
[1] Ghent University, RWTH Aachen University
[2] RWTH Aachen University
[3]Netherlands organisation for applied scientific research TNO
*email: jeroen.werbrouck@ugent.be

Abstract

With the emergence of Building Information Modelling (BIM), the construction industry is rapidly catching up with the digital revolution that has boosted productivity in virtually all economic sectors. In current practice, the focus of BIM lies on exchange of documents, often through proprietary formats exchanged using the Industry Foundation Classes (IFC). However, with web technologies such as RDF, OWL and SPARQL, a data- and web-based BIM paradigm becomes within reach. The decentralisation of data and decoupling of information and applications will enhance a more general adoption of Big Open BIM, and is expected to lower the BIM threshold for smaller companies that are active in different phases of the building life cycle. Since one of the promises of the Semantic Web and Linked Data is a highly improved interoperability between different disciplines, it is not necessary to reinvent the wheel for the setup of an infrastructure that supports such a network of decentralised tools and data. In this paper, we evaluate the specifications provided by the Solid project (Inrupt Inc.), a Linked Data-based ecosystem for *Social Linked Data*. Although the exemplary use case of the Solid ecosystem is decentralisation of data and applications for social network purposes, we notice a considerable overlap with recent ambitions and challenges for a web-based AECO industry (Architecture, Engineering, Construction and Operation). This includes standardised data representations, role- or actor-based authorisation and authentication and the need for modular and extensible applications, dedicated to a specific use case. After a brief introduction to Linked Data and its applications in the building industry, we discuss present solutions for building data management (Common Data Environments, multi-models, etc.). In order to translate these approaches towards a Linked Data context with minimal effort and maximal effect, we then review the Solid specifications for use in a construction-oriented web ecosystem. As a proof of concept, we discuss the setup of a web-service for creation and management of Linked Building Data, generated with the Solid-React generator. This application is envisaged as a bridge between the multiple data stores of different project stakeholders and the end user. It acts as an interface to a distributed Common Data Environment that also allows the generation of multi-models.

Keywords: Linked Building Data, Common Data Environments, Decentralisation, Solid

1. Introduction

The building industry is one of the most fragmented industries around the world. At the same time, it is also among the least digitised ones, only leaving 'Agriculture and Hunting' behind (McKinsey & Company, 2015). Although the recent upcoming of Building Information Modelling (BIM) has somewhat closed the gap, multiple challenges still need to be overcome before the sector reaches the full potential offered by digitisation. In other words, the use of integrated, interoperable data, exchanged through connected web services, or the reaching of 'BIM Maturity Level 3' as defined in the notorious BIM wedge (Fig. 1). The main goal of web-based BIM is to provide an answer to data islands that complicate lossless exchange and collaboration between disciplines that focus on the built environment. These disciplines form the AECO industry (Architecture, Engineering, Construction and Operation).

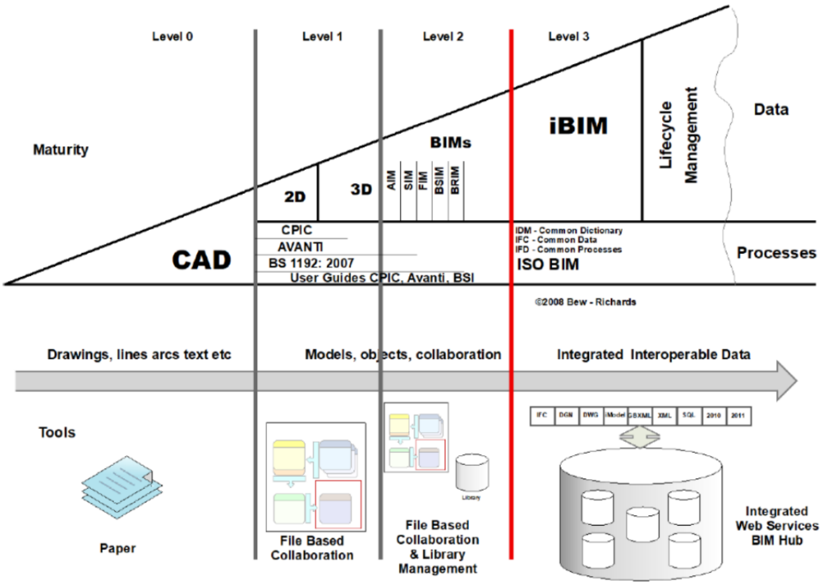


Figure 1: The BIM levels of Maturity as defined by BSI Standards Limited, 2013

Linked Data technologies are considered very promising to reach such high level of interoperability. These technologies rely on the Resource Description Framework (RDF)[1], which is a data model that has been standardised as part of the Semantic Web technology stack (Berners-Lee, Hendler, & Lassila, 2001). Using RDF, individual data concepts can be linked to one another in the form of triples. RDF triples can be understood as very basic sentences, linking a *subject* to an *object* with help of a *predicate* that states the exact relationship between the two. To ensure that each data item is uniquely identifiable over the web, it is characterised by a Uniform Resource Identifier (URI). This strategy, which is the main difference between RDF and other existing data models, allows to semantically enrich information in an open-world way: anything can be said about anything, which opens up possibilities for interdisciplinary collaboration. Furthermore, due to the structured representation of data in the form of a web-wide graph, digital agents are capable of semantically interpreting this data and using it for specific purposes with minimal human intervention. A distinction can be made between the terminology that is used to describe data (e.g. a taxonomy, a *type*) and the actual data individuals that are semantically connected using these structures (e.g. a specific object). The former is referred to as the TBOX ('Terminological'), the latter as the ABOX ('Assertion'). Knowledge models for defining conceptual domain schemas are mostly on a TBOX level. Such schemas are called 'vocabularies' or 'ontologies'[2] and give semantic meaning to certain data elements. The combination of multiple vocabularies allows to set up complex models of real problems.

The application of Linked Data concepts for the AECO Industry has been documented multiple times by now (Beetz, Van Leeuwen, & De Vries, 2005; Pauwels & Terkaj, 2016; Pauwels, Zhang, & Lee, 2017; Rasmussen et al., 2017), because it could seriously enhance interoperability between disciplines and collaboration between stakeholders. Linked Data allows to construct vocabularies for each related sub-discipline, connected with one another in a neutral format and distributed over multiple servers. This allows applications that are concerned with different aspects of the built environment to connect and exchange information without information loss. It also allows to link to open data on the web, such as contextual information (e.g. geospatial, governmental, historical or weather data). Furthermore, since vocabularies contain the information to interpret the data in a semantic way, automatic reasoning and rule checking comes within reach (Pauwels et al., 2017). With this in mind, several researchers are currently working on making Linked Data-based BIM more mature. First proposed in (Beetz et al., 2005), the setup of a Linked Data-based version of IFC was officially approved as the ifcOWL ontology (Pauwels & Terkaj, 2016). However, as ifcOWL covers the entire

[1] https://www.w3.org/TR/rdf11-concepts/, W3C
[2] https://www.w3.org/standards/semanticweb/ontology.html, W3C

IFC schema, it is very large and consequentially not really flexible to deal with topics that are not sufficiently covered in the IFC standard, such as existing buildings, Geographic Information Systems (GIS), Facility Management (FM) or circular economy. A new paradigm is therefore proposed by the W3C Linked Building Data Working Group[3], targeting the development of more modular vocabularies that each address a specific building-related topic (Rasmussen et al., 2017). The main advantage of such modular Linked Data vocabularies over traditional, monolithic, domain-specific information models such as the IFC schemas is their modularity, which increases the flexibility to address specific challenges.

While much research and standardisation has been done regarding the Semantic Web, in general as well as for construction, the number of applications that effectively use its potential remains limited: Linked Data technologies have a steep learning curve and there is quite an implementation threshold for developers to actively contribute to an interconnected network of online applications (Verborgh, 2018). In order to stimulate the worldwide developer community, and to separate personal data from the applications that use it, the recent Solid project (Social Linked Data) was founded (Mansour et al., 2016). It aims at a decentralised ecosystem for social web applications, in which users own their data themselves and allow external (micro)applications to use it for a certain (social media) purpose. However, social media are just one use case picked by the Solid team to illustrate its concept. The same set of specifications and tools can be used for other domains as well, especially for disciplines as fragmented and decentral as the construction industry.

Multiple research projects are focusing on the development of knowledge models for describing the built environment in a Semantic Web context. In order to implement these knowledge models and move towards BIM Maturity Level 3, usable applications need to be developed. Modular web applications for the building industry, able to communicate with each other and exchange disparate data with use of HTTP and JSON, were recently re-introduced as 'BIM bots'[4], often built using the BIM bot compliant BIMserver framework (Beetz, van Berlo, de Laat, & van den Helm, 2010), a well-known implementation of Model Servers that is based on IFC. Going one step further, the idea of BIM bots could be extended with Linked Data, broadening their range towards topics that are not typically covered by IFC. As the Semantic Web technology stack offers the possibility to connect various domains, there is no need to start a specific Linked Data ecosystem for construction. With this in mind, this paper discusses the use of the specifications provided by the Solid project. As we consider a way for collaborative project data management the first step for a network of Linked Building Data tools, a prototypical management service is implemented within the Solid ecosystem as proof of concept, using the Solid-React generator, which hides the complexity of authentication, authorisation, data storage etc.

2. Collaboration strategies for building projects

Different strategies exist by now to reach a more streamlined collaboration within building projects. A Common Data Environment (CDE) is a virtual storage location for collecting and managing documentation of building projects, mostly offered as a cloud service. Because all project information is managed in this common environment, the chance of misunderstanding and information loss is strongly reduced. Access to certain documents can be defined by the project's Information Delivery Manual (IDM), based on the international BuildingSMART standard for bundling and structuring Information Requirements (IR). Examples of commercial CDEs are, for instance, Autodesk's BIM 360 and Trimble Connect. CDEs can be optimised to work with certain data formats, either proprietary or open. Standards such as IFC allow information to be exchanged between applications from different software vendors, which, in most cases, use proprietary data formats natively. The BIMserver platform (bimserver.org) implements IFC in a model server and allows developers to build web services or plugins that can be connected to the shared IFC database and exchange data via a common API (e.g. BIMSie (van Berlo, 2015)). Recent developments show that the main CDE suppliers are open to develop a standardised open API for CDEs. This initiative just recently started as a follow up from the German DIN SPEC (91391-1/2) initiative that defines the features and expectations from a CDE.

[3] https://w3.org/community/lbd/, Linked Building Data Community Group
[4] http://bimbots.org/, Van Berlo, L.

An approach related to CDEs, but more focused on the container structure in which project information can be stored, are the so-called multi-models. The most recent development in this domain is the Information Container for Data Drop (ICDD), which is in the final stage of standardisation as ISO 21597. It is the successor of the Dutch COINS standard and follows a tradition of ontology-based multi-model management (Gürtler, Baumgärtel, & Scherer, 2015; Schapke, Katranuschkov, & Scherer, 2010; Törmä, 2013). In its own words, ICDD has been developed '*in response to the need of the construction industry to handle multiple documents as one information delivery or data drop'*. Its internal structure is based on two ontologies: a Container ontology and a Linkset ontology. As the former defines the classes and properties used for description of metadata about the container, the latter provides the definitions for the semantic links between documents. The standard allows to refer to identifiers on a sub-document level, such as individual IFC GUIDs or pixel zones within an image. An ICDD container can be considered a semantically connected 'dump' folder with the available project information, and can, for example, be used when project data needs to be transferred from one project stakeholder to another. A container in *.iccd format (using a ZIP compression) has a fixed structure, containing subfolders with the main ontologies, the 'payload documents' (e.g. imagery and IFC files) and the 'payload triples' for the relationships between those documents. The main folder contains an *index.rdf* file that contains the documents of the project and some metadata. The *content.rdf* file that is stored in the 'payload triples' folder can also refer to external documents or URIs. An overview of the ICDD structure is given in Fig. 2, depicting the folder structure and a subset of a linkset in Turtle format.

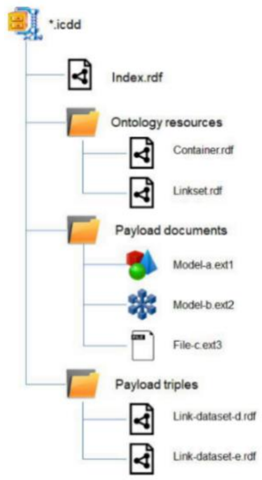


Figure 2: Structure of an ICDD container (source: ISO 21597-1)

In this section, a brief introduction was given to CDEs and the ICDD standard for multi-model containers. While CDEs focus on a cloud environment for enhanced collaboration, Linked Data-based multi-models allow to establish specific links between project documents and sub-document information. A Linked Data-based CDE would need to combine the possibilities offered by CDEs, while allowing to establish links between RDF data and documents, on a fine-grained data level. This way, project sources such as imagery, point clouds, geometry etc. can be linked with RDF graphs about topology, products and properties. In the next section, we review the specifications of the Solid ecosystem for use in such a Linked Data-based CDE.

3. Solid specifications

The initial use case of the Solid ecosystem is social media. Decoupling of applications and data lets users stay the owner of their own data and allow the applications that suit their needs the most to access that data. From a more general perspective, it embodies a movement that aims to realise the web 'as originally envisaged' by Tim Berners Lee (Berners-Lee, Dimitroyannis, Mallinckrodt, & McKay, 1994; Berners-Lee et al., 2001): personal data storage, standard communication between apps and the use of a ‘universal’ data format in the form of RDF[5]. The decoupling of apps and data is as relevant for the building sector as it is for social data. The BIMserver realises this within context of IFC; the Solid framework could be a candidate for doing this in a Linked Data context. In the following section, we review the main specifications for the Solid framework[6], and suggest how they could be implemented for projects dealing with the built environment.

3.1 Identification and authentication

In Solid, identification of actors happens through WebIDs[7]. In Section 1, it was stated that in Linked Data, every ‘resource’ is identified through a unique identifier over the web, a URI. Applied to WebIDs, this means that any actor can have their own URI, that can relate to other resources (e.g. personal data or other people’s WebIDs) and be linked to by other resources as well. This generates a global ‘social graph’ with fundamental relationships between a person, his data and other people’s data. Within Solid, the WebID is used as a URL (Uniform Resource Locator), which is a specific type of URI that, apart from identifying the resource, also allows to access it. An example of a WebID could be *https://jwerbrouck.solid.community/profile/card#me.* It identifies both the resource that should be included in triples that link to this person, and the web address that allows to access his personal data card. This card is part of the ‘datapod’ of the actor: the server (personal or hosted by a providers) that contains an inbox, a public folder and a private folder. According to the specifications, a 2019 update will include a section where access rights for third-party applications can be managed: read, write, append and control. At the time of writing, this is only managed by logging in to the application with the personal webID. This system of datapods that allow specific apps to access the data is the main difference with current social networks, that require users to upload their data. The WebID also serves as the basis for authentication of actors, instead of usernames, by making use of the WebID-TLS protocol[8] and cryptographic certificates generated by the browser.

3.2 Authorisation

To determine whether a certain actor (person or application) has access to particular data, an RDF-based authorisation mechanism called ‘Web Access Control’ (WAC) (Hollenbach, Presbrey, & Berners-Lee, 2009) is used. Actors can be identified by their WebIDs, which are stored in *.acl graphs that state which webIDs should be allowed to read or update data. The specification also allows to refer to groups of users instead of specific ones. An *.acl file can be linked to an entire folder (such as the basic folders for public and private data), but can also be mapped in a more fine-grained way to subfolders or individual files or RDF graphs. Currently, the specification does not allow for mapping on resource level, which could be beneficial for Linked Data-based building projects (Oraskari & Törmä, 2016).

3.3 Content Representation

In general, datapods make a difference between Linked Data resources (e.g. in the form of Turtle, JSON-LD, etc.) and non-Linked Data resources (e.g. imagery, PDF files, etc.). All the resources are grouped into subfolders of either the private or the public data folder. As indicated in section 3.2, access rights can be regulated per graph or document, based on the .acl specification.

[5] https://inrupt.com/, Inrupt
[6] https://github.com/solid/solid-spec, Inrupt
[7] https://www.w3.org/2005/Incubator/webid/spec/identity/, W3C
[8] https://www.w3.org/2005/Incubator/webid/spec/tls/, W3C

3.4 Solid SDK

As indicated in Section 1, the number of applications that use Linked Data remains limited. Since a decentralised and distributed ecosystem such as Solid relies on third party developers for application development, it needs to lower this development threshold. With this in mind, a dedicated Software Developer Kit (SDK) for programming in React and Angular is provided. This includes a generator that preconfigures the solid specifications (e.g. for security settings), so developers can focus on the functionality they want to implement, instead of implementing the specifications themselves. It also includes the Comunica framework (Taelman, Van Herwegen, Vander Sande, & Verborgh, 2018) for querying Linked Data on the web, with SPARQL (SPARQL Protocol and RDF Query Language)[9] or its less verbose and more accessible variants GraphQL-LD (Taelman, Vander Sande, & Verborgh, 2018) and LDflex (Verborgh, 2018). The use of these more accessible query languages is also expected to improve the development rate of Linked Data applications.

3.5 Solid for construction

The above mentioned specifications of Solid could easily be implemented for an AECO-oriented CDE, possibly extended towards an ecosystem of Linked Data BIM bots. Future research should determine the optimal configuration, although for this first paper we propose a preliminary approach, which will also be used in the proof-of-concept application of Section 4.

In this workflow, the project manager creates a private project subfolder in his or her datapod. All project stakeholders have their own datapod as well, and get the URI of the main project folder of the manager. This does not mean that they have access to the contained files, as this can be managed individually. This project folder should contain at least two graphs in the private data section. The first one defines the minimal project information; the ‘skeleton’ of the project in the form of its topology. We suggest to use the modular Building Topology Ontology (BOT) (Rasmussen et al., 2017) as recommended by the W3C Linked Building Data Community Group. BOT allows to identify different zones within a building (site, building, storey, space) and define the relationships between them. The second graph contains the WebIDs of different stakeholders and their function(s) in the project. This stakeholders graph will be used to define access rights based on the role in the project. In case a handover of the project data happens, or roles are switched within one project, access rights can therefore immediately update.

Project stakeholders then create a project folder in their own pod as well, and upload the information that is their responsibility, while linking it to the general project URI from the manager. They can request access to project information from other stakeholders, to be able to link to this information as well. Granting access to other project information might be done by the manager (who has access to the entire project database by default) or by the responsible stakeholder. This way, an interlinked, virtual environment starts to exist, which links the data and documents from the project stakeholders into a web-based graph; a Linked Data-based Common Data Environment. Ideally, only binary information (imagery, point clouds) is stored as documents, while other information such as topology and product data is stored in an RDF graph. However, the described workflow also supports a more traditional document-based approach: a project management app that implements the ICDD ontologies could easily generate an ICDD dump file of the project, mirroring the distributed online model.

Apart from this rough workflow, the Solid SDK and implementation of, for example, GraphQL-LD to ease querying, could significantly stimulate development of Linked Building Data applications. A general workflow for aligning such applications needs to be made in the future, so they can automatically communicate with one another and exchange information that is required for a certain use case. This workflow could be based on the IDM and MVD specifications and include a method to describe use cases in a modular way, where tools can be chained together, automatically validating their inputs and outputs, for example with use of SHACL (Shapes Constraint Language)[10]. Such tools can

[9] https://www.w3.org/TR/rdf-sparql-query/, W3C
[10] https://www.w3.org/TR/shacl/, W3C

then use the RDF data in the distributed project pods for advanced reasoning, simulation, model enrichment etc. At the moment, however, the first step is the setup of a prototype application for basic management of building data.

4. Proof of concept: ConSolid

In this section, the workflow discussed in Section 3.5 will serve as a guideline for the development of a rudimentary application for building data management, which is entitled ‘ConSolid’ (Construction Solid)[11]. In the ideal case, the ConSolid app aids in the following building project management topics:

- Configuration of the building project and its topology
- Semantic enrichment of a building project with geometry, product data and properties
- Configuration of the stakeholders and their role within the project
- Uploading documents to building project folders
- Linking document-based information to each other and to RDF graphs
- Validating the distributed model with predefined validation shapes (e.g. SHACL)
- Querying building project information
- Generating ICDD project containers

The test application was generated with the Solid React generator[12]. As the development is work in progress, not all functionality has been implemented at the time of writing: initial work has focused on implementing project and topology creation, role assignment and uploading, linking and querying of project information by the project manager. Semantic enrichment of the project with product data, properties and geometric information has not been implemented yet. Strategies to integrate SHACL validation in the ConSolid tool are discussed in (Werbrouck, Pauwels, Senthilvel, & Beetz, 2019).

4.1 Basic functionality

The generated application includes login functionality with one’s WebID. After logging in, the WebID is stored, which allows the application to perform actions with the data stored in the user’s pod. In the current implementation, we distinguish 3 main tabs, apart from the general ‘Home’ and ‘Profile’ tab: ‘Topology’, ‘Roles’ and ‘Connect’, respectively for managing the basic information of the building, stakeholders and their roles and the connection of distributed project data.

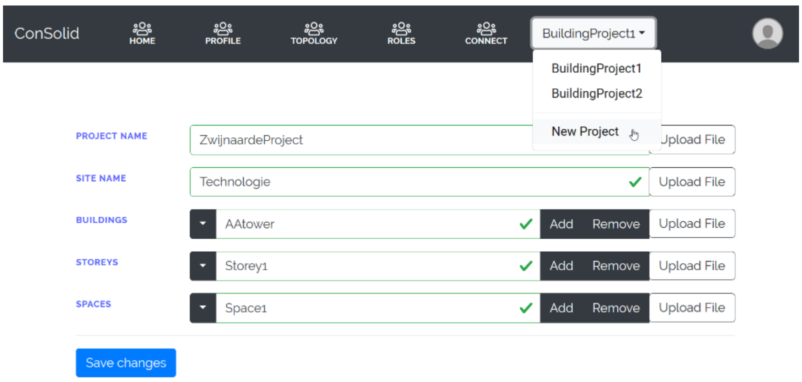


Figure 3: Loading a building project from a user’s datapod in the ‘Topology’ tab

[11] The project code is available at https://github.ugent.be/jmauwerb/solid-cde
[12] https://solid.inrupt.com/docs/writing-solid-apps-with-react

4.2 Project Topology

If the user is the owner of any project, it can be selected in the navigation bar and loaded from the distributed pods of the stakeholders (Fig. 3). The basic building topology is then displayed in the 'Topology' tab, where it can be updated. Documents may be uploaded to the pod and linked to particular zones in the building, as an alternative to the more advanced linking in the 'Connect' tab. If no projects have been created yet, a new project can be created from scratch, stating the basic topology and setting the creator of the pod as the project manager. As mentioned earlier, the ontology that is used for topology description is BOT, although other ontologies such as ifcOWL could be used as well.

4.3 Role management

The 'Roles' tab allows the project manager to assign certain roles to certain WebIDs. These roles are stored in a graph in the main project pod (using FOAF) and can be used for managing access rights. A schema may be developed with some standard access rights that are mapped to certain roles, to automatically set the rights that occur the most. Role groups can be configured from this data, which means a more flexible approach than person-based access rights.

4.4 Data connection and container generation

In the 'Connect' tab, the user can upload files to their project pod. A stakeholder that is logged in may upload files to her pod. Project files to which the user has access rights can be linked to one another, as documents as well as on sub-document level. As indicated in Section 3.3, these project documents can be Linked Data as well as non-Linked Data.

In order to allow optimal linking of documents and triples, different strategies may be used for different file formats. Since the ICDD specification does not state how sub-document identifiers for certain document formats are to be defined, there is no agreed upon system to refer to IFC GUIDS, pixel zones etc. As this is a separate issue that is not considered part of this work, this prototype is currently limited to linking and displaying RDF graphs and imagery. In future versions, 3D model viewers, text editors, etc. could be implemented as well to support a broader variety of documents.

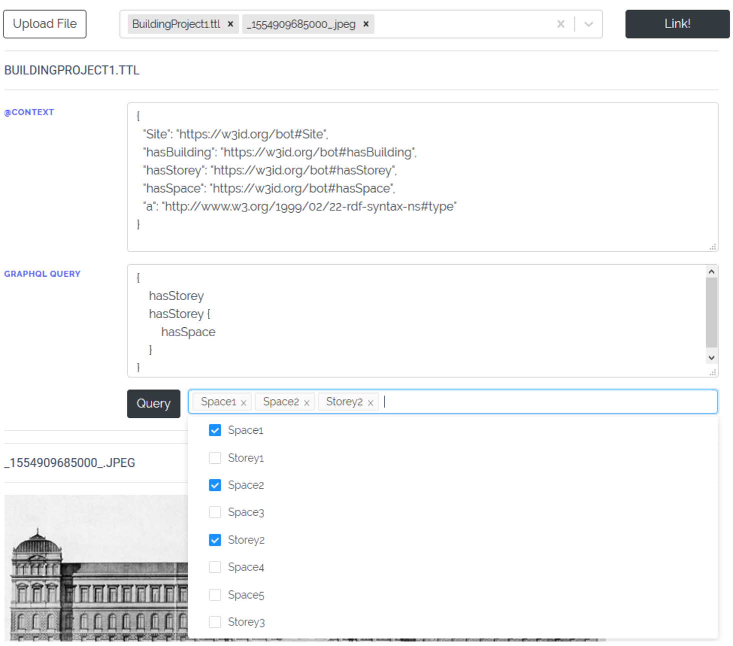


Figure 4: uploading and linking documents in the 'Connect' tab. Linked Data files may be queried with non-specialist languages such as GraphQL-LD or LDflex.

To simplify the querying of the Linked Data files, a test engine for GraphQL-LD has been implemented (Fig. 4). This means that an end-user does not need to know the details of Linked Data to query the available information. The query results can then be individually selected to link to other RDF resources, documents or sub-document identifiers. As Solid pods also follow a container-like structure, the implementation of functionality for generating an ICDD container should be quite straightforward.

4.5 Testing

Full testing of the tool's functionality has not happened at the moment of writing, although the different modules (project creation, topology, querying) have been tested separately and iteratively during the development process. It lies within the ambitions to simulate a more complete project when the above-mentioned modules are more tightly integrated with one another.

5. Conclusion and Future Work

5.1 Conclusion

In this paper, we suggested the use of Linked Data for semantically connected Common Data Environments. Because of the universality of RDF, such CDE could play a central role in a network of modular applications that each envisage a certain activity in the Building Life Cycle. The scope of such applications is therefore not limited to 'typical' construction activities, but could also include adjacent domains such as historical or geographical data, Facility Management, circular economy etc. Modular domain models, as proposed by the LBD Community Group, enable a more flexible approach to projects that work with disparate data. It was shown that the idea behind the Solid ecosystem is similar to the concept of BIM bots, but then in a Linked Data environment. A brief overview of the basic specifications offered by this ecosystem for social linked data was given, and the potential for managing Building Projects was illustrated. To finish, a prototype application 'ConSolid' was discussed, using the SDK that preconfigures the specifications for the application. This service is still in a very early development phase and thus highly experimental. Nevertheless, some basic functionality shows that a decentralised management of building information is achievable with the available technology stack.

5.2 Future Work

As this work is only an introduction, future work might focus on multiple aspects. One aspect is further develop the ConSolid application towards a more mature tool that can be used in practical situations. Apart from the basic implementation discussed in Section 4, vocabularies for describing product information and properties need to be implemented to be able to create realistic projects. This is a prerequisite for testing the overall capabilities of the use case in a later development stage. Another focus should lie on how multiple tools can access the building project data and communicate with one another. For example, establishing a link with (existing) modelling packages will make the creation of a basic Linked Building Data model more intuitive. Due to the decentralisation principle, other web applications that are authorised to fetch the project data may further enrich or analyse the project, e.g. by performing building performance simulations. When many tools are each dedicated to one small task, they could be used as atomic building blocks in a tool chain that addresses larger use cases. Semantic Web technologies such as SHACL allow validation of the information that is exchanged in such chain. Having a way to configure and connect multiple, modular tools should also allow building disciplines that lie beyond construction to collaborate and use the same data. However, such scenarios require a more thorough interlinking of information on data level: rather than being stored in files, the available information needs to be represented in RDF format as much as possible.

With this in mind, we hope this work can contribute to the advancements of the BIM community towards an open BIM practice that is characterised by integrated web services and interoperable data.

Acknowledgements

The authors would like to acknowledge the support by both the Special Research Fund (BOF) of Ghent University and the BIM4REN project, which has received funding from the European Union's Horizon2020 Research and Innovation Program under grant agreement No 820773.

References

Beetz, J., van Berlo, L., de Laat, R., & van den Helm, P. (2010). BIMserver. org–An open source IFC model server. *Proceedings of the 27th CIB W78 Conference on Information Technology in Construction*, 8.

Beetz, J., Van Leeuwen, J. P., & De Vries, B. (2005). An Ontology Web Language Notation of the Industry Foundation Classes. *Proceedings of the 22nd CIB W78 Conference on Information Technology in Construction*, *2006*, 670. Technical University of Dresden.

Berners-Lee, T., Dimitroyannis, D., Mallinckrodt, A. J., & McKay, S. (1994). World Wide Web. *Computers in Physics*, *8*(3), 298.

Berners-Lee, T., Hendler, J., & Lassila, O. (2001). The Semantic Web. *Scientific American*, *284*(5), 28.

Gürtler, M., Baumgärtel, K., & Scherer, R. J. (2015). Towards a workflow-driven multi-model BIM Collaboration Platform. *Working Conference on Virtual Enterprises*, 235. Springer.

Hollenbach, J., Presbrey, J., & Berners-Lee, T. (2009). Using RDF Metadata to enable Access Control on the Social Semantic Web. *Proceedings of the Workshop on Collaborative Construction, Management and Linking of Structured Knowledge (CK2009)*, *514*, 167.

Mansour, E., Sambra, A. V., Hawke, S., Zereba, M., Capadisli, S., Ghanem, A., … Berners-Lee, T. (2016). A Demonstration of the Solid Platform for Social Web Applications. *Proceedings of the 25th International Conference Companion on World Wide Web*, 223. International World Wide Web Conferences Steering Committee.

McKinsey & Company. (2015). *Imagining Construction's Digital Future*. Retrieved from https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/imagining-constructions-digital-future

Oraskari, J., & Törmä, S. (2016). Access Control for Web of Building Data: Challenges and Directions. *EWork and EBusiness in Architecture, Engineering and Construction*, 45.

Pauwels, P., & Terkaj, W. (2016). EXPRESS to OWL for Construction Industry: Towards a recommendable and usable ifcOWL Ontology. *Automation in Construction*, *63*, 100.

Pauwels, P., Zhang, S., & Lee, Y.-C. (2017). Semantic Web Technologies in AEC Industry: A Literature Overview. *Automation in Construction*, *73*, 145.

Rasmussen, M., Pauwels, P., Lefrançois, M., Schneider, G. F., Hviid, C., & Karlshøj, J. (2017). Recent Changes in the Building Topology Ontology. *LDAC2017-5th Linked Data in Architecture and Construction Workshop*.

Schapke, S. E., Katranuschkov, P., & Scherer, R. J. (2010). Towards ontology-based management of distributed multi-model project spaces. *Proceedings of the 27th CIB W78 Conference on Information Technology in Construction*.

Taelman, R., Van Herwegen, J., Vander Sande, M., & Verborgh, R. (2018). Comunica: a modular SPARQL Query Engine for the Web. *International Semantic Web Conference*, 239. Springer.

Taelman, R., Vander Sande, M., & Verborgh, R. (2018). GraphQLLD: Linked Data Querying with GraphQL. *ISWC2018, the 17th International Semantic Web Conference*.

Törmä, S. (2013). Semantic Linking of Building Information Models. *2013 IEEE Seventh International Conference on Semantic Computing*, 412. IEEE.

van Berlo, L. (2015). BIM Service Interface Exchange (BIMSie). Retrieved from https://www.nibs.org/page/bsa_bimsie

Verborgh, R. (2018). Designing a Linked Data Developer Experience. Retrieved 25 April 2019, from https://ruben.verborgh.org/blog/2018/12/28/designing-a-linked-data-developer-experience/

Werbrouck, J., Pauwels, P., Senthilvel, M., & Beetz, J. (2019). *A checking approach for distributed building data*. Presented at the 31st Forum Bauinformatik, Berlin, Germany.

A Proposed Model for Digital Transformation of Requirements Management in the Design of Healthcare Facilities

Ahmed Alnaggar*, Eleni Papadonikolaki
The Bartlett School of Construction and Project Management, UCL
* Email : ahmed.alnaggar@ucl.ac.uk

Abstract

The design complexity of healthcare buildings is ever-increasing, and due to the various codes, regulations, and client requirements that these buildings must comply with, the process of manual requirement management across the asset lifecycle becomes costly, labour intensive, error-prone and time-consuming. This paper proposes a theoretical process model for the digital transformation of requirements management for healthcare facilities. The model is titled "Automated Rule-Based Code Checking" (ARBCC). ARBCC process model is based on a comprehensive review of related academic work, commercial software, and government initiatives that investigated the automation of requirements management. ARBCC's approach is based on transferring the healthcare project requirements into rules that are machine readable, and can be checked using computer software, then use Building Information Models (BIM) to check if these rules have been correctly adhered to in the design of the healthcare facility at hand. The model consists of four phases: 1- Initiation: In which we identified and collated the rules and regulations of healthcare buildings in the UK. 2- Planning: In this phase, the extracted rules should be classified according to the RIBA stage, then the rules should be either extracted or written for each requirement, and the required BIM Level of Development (LOD) should be identified to check each rule. 3- Implementation: In this phase, the actual automated check of the created rules is performed versus the BIM model. 4-Assessment phase: In which the results of the check is analysed and any non-compliance is automatically reported using the compliance check software. This paper forms the initial theoretical base of an ongoing study that investigates the digital transformation of requirements management. The next phase of the study will be to implement the ARBCC model for a sample of the identified healthcare codes and regulations and analyse the findings.

Keywords: Digital Transformation, Requirements Management, HealthCare Design, BIM

1. Introduction

The architecture, engineering and construction (AEC) is an information-intensive industry by nature because every construction project requires the creation, dissemination, storage and analysis of extensive information about the built assets and spaces. The construction management literature has a lot of examples of problems associated with information management in construction projects with a recurring theme being poor management of design requirements throughout the project lifecycle (El Kharbili, 2012). For instance, the lack of common language between clients and design teams creates misunderstanding and ambiguity in identifying and defining client requirements. This ambiguity later requires more design iterations to clarify issues and more Requests of Information (RFI's) and if not appropriately managed, it ultimately involves re-designing or even re-constructing certain parts or systems of the building which is costly and time-consuming. This paper is part of an ongoing study to understand and address how digital transformation can support requirement management.

Building requirements come from different sources such as building regulations, codes and standards (Cheng et al., 2007), and these sources of requirements are often written in a way that is not machine-readable making it a mandate to check their compliance manually across all the teams and at all stages of the project. This manual check process is tedious, laborious, and prone to human errors. However, even with correct requirement identification, these requirements are often very complicated and require excellent communication between involved teams including architects, design consultants, construction engineers, subcontractors and facility management professionals. These teams are usually dispersed over a wide area of geographic locations creating problems with traceability and dissemination of the design information. Different teams also use different technology platforms to manage project information causing communication and collaboration to be inefficient. These issues have largely contributed to the construction industry's chronic problems of having cost overruns (Mahaney, and Lederer, 2010), severe delays (Tesch et al., 2007), and poor quality, and a lot of these issues are associated with the complexity of requirement management process through the building lifecycle.

The complexity of the requirements management process in construction stems from the need to collect different types of requirements from various sources. For example, functional requirements including client requirement that ensures the building will satisfy its business need, and stakeholder's requirements that ensure the building will be fit to serve its occupants and the broader community in the best way. Some of these requirements are sometimes contradictory (Eastman et al. 2009) and require good coordination and communication among stakeholders. Otherwise, it negatively affects the quality of the overall design (Bouchlaghem et al., 2004). Furthermore, requirement management involves collecting information in different formats including drawings, bills of quantities, spreadsheets, documents making it difficult to manage these requirements due to interoperability issues (Lee, 2012) between different systems used to manage information. The requirements also change during the project, as the design develops, it happens almost in all cases that the client would suggest some design changes, and these changes will have other consequences in other areas of building design. For example, a proposed space remodelling change by the client would require consequent changes in the Heating Ventilation and Air Conditioning (HVAC) and Mechanical, Electrical and Plumping (MEP) systems design in all remodelled spaces. These changes if not managed properly cause delays and increase the risk of rework in the project. Finally, the process of compliance check and assessment between the design/implementation and the original requirements span across all stages of building lifecycle (Kiviniemi et al., 2004), and it is done repetitively (Davis and Zweig, 2000). Lack of effective management of this information across the lifecycle causes inefficacies (Yu et al., 2005) in information access and compliance across stakeholders (Fernie et al., 2003).

In healthcare projects, the complexity of project requirements is even more significant in most of the cases (Cysneiros, 2002). This added complexity is caused by the different functional requirements that a hospital should satisfy (Doulabi and Asnaashari, 2016) including inpatient and outpatient functions, diagnosis and treatment, administrative, emergency, teaching and research and hospitality functions. Furthermore, modern hospitals use a vast range of diagnosis and treatment specialist equipment that adds another technical layer of design complexity on top of the normal building services such as HVAC, MEP, Information and Communication Technology (ICT) and safety and security systems. Historically, the compliance assessment/check for these requirements was done by using manual processes, because the information came in different formats and was mostly paper-based, this was time-consuming, yielded low-quality outputs of the information check (Jallow et al. 2014), and was resource intensive in terms of labour and time.

This paper deals with the emergence and vast spread of the concept of digital transformation that has become increasingly important in the Architecture, Engineering Construction, and Operations (AECO) industry especially in the last decade. At a global level, the unprecedented global challenges of ever-increasing urbanisation, climate change and open international competition called for new ways of designing, constructing and operating buildings and infrastructure (Zhang et al., 2018; Elliot, 2011). At a national level, digital transformation is considered a strong enabler for seizing the opportunities of the digital economy, building and managing the increasingly complex built environment, maximizing on the capacity and skills of the AECO sector workforce, and creating new business models based on emerging technology (Matt, Hess & Benlian, 2015). Building Information Modelling (BIM) as a digital transformation tool with its digital capabilities, collaborative philosophy, and systematic information exchange processes provided an excellent opportunity to automate the process of requirement compliance assessment, and Machine learning (ML) is another digital transformation tool that can be used for translating the complex requirements into rules that can be checked using the BIM model.

Based on that, this paper will investigate an automation framework based on BIM that can be used to automate the process of requirements management and the opportunities and challenges associated with this in the construction of healthcare buildings.

2. Methodology

This paper presents a theoretical model for the digital transformation of requirements management in healthcare facilities. The model is mostly based on a literature review of related academic studies, industry reports, government regulations and commercial software reports. These sources covered different aspects of the requirement management, and automation, and formed an adequate base for an overall theoretical model. This paper forms the first phase of an ongoing study to investigate the digital transformation of requirements management of healthcare buildings.

The overall study will rely on Design Science Research (DSR) methodological approach. DSR is known to be an effective methodology in solving real-world problems and also contribute to the development of theories and models about these problems (Miah et al., 2014). Unlike other conductive research methods that require the test of an established theory using the collected data (Oyegoke, 2011), DSR uses an inductive approach to create models and frameworks that help in framing new theories. Hence, the assessment approach of DSR research is to test the resulting artefact and appraise its value using an iterative process that is very similar to the design process. Subsequently, further work is ongoing in the study to apply and test the framework using the identified UK healthcare regulations.

3. Theoretical background and related work

Historically, the construction industry, has always suffered from inadequate project management practises that caused construction projects to be over budget or delayed. In some cases, projects meet the budget and time constraints but fail to meet either the client requirements or the need of the ultimate users (Potts, 2008). For example, in the UK, Heathrow Terminal 5 project suffered from many problems by the start of its operation, these problems resulted in the cancellation of flights, and loss of passengers' luggage (Brady and Davies, 2010). The analysis of the causes of these problems indicated that many of them were due to lack of proper requirements management of the project throughout its design and construction phases. These inefficiencies in requirement management included insufficient involvement from project stakeholders, lack of adequate communication practices of client requirements, failure to incorporate continuous quality assessment in each phase of the building lifecycle, and poor risk management among design and construction teams. This highlights the need of innovative approaches to ensure the client requirements are incorporated within the project management of these complex projects to ensure the projects: First meet its constraints in terms of budget and schedule but equally important, to meet the client and user requirements.

According to the plan of work (PoW) of the Royal Institute of British Architects (RIBA), the first stage of any building construction should be stage 0, i.e. "strategic definition" (Architeture.com, 2019). This stage commences by defining the project's business case and core client requirements. The identification of the core client requirements at this stage is the start of the requirements management process. The Association for Project Management in the UK (APM) defines requirements management as: "The process of capturing, assessing and justifying stakeholders' wants and needs."(Apm.org.uk, n.d.) This definition breaks the process down into three stages: 1- Capturing, i.e. collecting different requirements from different stakeholders and governance bodies, and analysing the requirements to identify areas of conflict, gaps and overlaps. 2- Assessing the requirements and separating the obligatory regulations from the "good to have requirements". 3- Justifying that the actual building design complies with the final requirements as a baseline for the project. Each of these steps requires collecting and managing information from serval sources and in several formats which makes it a too complicated process to be done manually especially with the ever-increasing complexity of buildings (Pauwels et al., 2011), and the scarcity of resources including time and cost of skilled labour. That's why the automation of requirement management has attracted a lot of interest from industry, government bodies and academia.

Following a survey of related work, the automated rule-based requirement management research which took two main streams. The first stream investigated the transfer of the text in the building codes, regulations and client requirements into machine-readable rules that can be checked using computer software. The second stream is concerned with investigating how to perform the actual checking of the automated rules with the aid of BIM. Following is an overview of the work done in this area in the two mentioned streams.

3.1. Translating the codes and requirements into rules

This research stream focuses on ways to transfer the text documents holding the codes, regulations and client requirements to a computer readable form to facilitate its automated check using the software. Today, the building regulations and client requirements are typically written in a way only understandable by humans (Jallow et al. 2014), and it also requires domain knowledge to interpret and understand its semantics due to its lack of clarity and sometimes its complexity. Several methodologies have been used to automatically interpret the regulations into a format that can be understood and used by computers which is called codification process. For example, a mechanism called RASE (Requirement, Applicability, Selection, Exception) can automatically transfer the text in the requirement documents into rules using the semantic web without the need of programming skills (Hjelseth and Nisbet, 2010) (Hjelseth and Nisbet, 2011). (Salama & Gohary (2011) developed a five-step approach with a preliminary model of transferring text into rules using deontic logic which is a branch of modal logic that is concerned with capturing logical features of a document. (Zhang & El-Gohary, 2012) Proposed the use of knowledge extraction to create rules out of the regulatory documents. This knowledge extraction involves the use of Natural Language Processing (NLP) and its associated techniques like phrase structure grammar (PSG) and dependency grammar (DG) for extracting information from complex sentences however the study was primitive and had a limited sample of text, and it was conducted using only one sort of requirements (Fire regulations).

Other research done in this domain used automated rule engines to compare the regulations with the model. Beach et al. (2013) extended the use of RASE by the use of the open source rule engine called DROOLS. The approach proposed to add metadata to the rules, and transfer it into a format understood by DROOL engine using a rule compiler then use the engine to determine if the rule is in scope for the project to be checked and second if the result of checking the rule a pass or a fail. However, the test for this approach was done using selected rules from the Building Research Establishment Environmental Assessment Method (BRAEEM) framework, and no extensive testing has been reported in this study. Nawari (2013) transferred the smart codes developed by the International Code Council (ICC) using language integrate query language (LINQ) to extract the information from the smart code efficiently, and then compare the extracted rule to the BIM model using ifcXML exchange format. The main theme of almost all of these efforts is that they all used a particular regulation and applied their proposed mechanisms to a small sample of the text of the selected regulation.

3.2. Preparing the BIM Model

After translating the codes, regulations and requirements to rules, BIM is used to check and assess if the building complies with these rules. However, to do that, the BIM model needs to be adequate for such a task. There are two main aspects of model preparation in order to be suitable for the check of the identified rules. First, data in the model should be in a suitable format to allow for the check, this format or view of the model is generally known as a Model View Definition (MVD) (Zhong et al., 2012). The second aspect is that the model view should include enough details about building spaces and assets to allow for the check, i.e. the Level of Development (LOD) should be adequate for the check. Following is a brief introduction to these concepts:

3.2.1. Model View Definition (MVD)

BIM contains large and diverse datasets about the building and its different assets. Consequently, there is no one rule or a ruleset that would need to check all the data in a BIM model at one instance. That is why to check a certain rule, a subset of the BIM model is extracted that fits the checked rule. This subset is called a Model View Definition (MVD) (Han et al., 1998). For example, a ruleset that is concerned with fire safety would require the areas of the model that are concerned with fire exits, fire safety systems and so on, and this rule would require a different view of the model from another ruleset that for example is concerned with checking accessibility requirements. The IFC (Industry Foundation Class) standard by BuildingSmart is the main model view definition standard. It was developed to allow for interoperability among different BIM authoring software (Liebichet al., 2006), and to allow a specific subset of building data to be extracted from the model to fit a particular need for this data. Therefore, IFC has provided a good ground for performing this automated rule check because it allows extracting views from the model that are best suited with the specific rule in hand.

3.2.2. Level of Development

Another BIM aspect that has a vital role in implementing a rule-based requirement management system is the level of development (LOD). LOD is developed by the BIMforum to identify the depth of information about assets that BIM model must include in different stages of building lifecycle (Solihin and Eastman, 2015). The LOD has two main categories; first, the Level of Information (LoI) that is concerned with the data aspect of the asset in the BIM model, and what details should be there about the asset in every phase of the building lifecycle. Second, the Level of Detail which is concerned with the geometry/graphical aspect of the assets in the model. Currently, there are five levels of LOD in industry, namely LOD 100 to LOD 500 in the US system (Solihin and Eastman, 2015). Each LOD has a full representation of the state of the data and geometry of the BIM model at a particular phase of the building lifecycle. This representation is usually identified in terms of its IFC parameters (Hietanen and Final, 2006). The importance of the concept of LOD for a rule-based system is that it makes it easier and quicker to identify which rules can be checked in which phase of building lifecycle according to the BIM model's LOD. For example, in a healthcare facility, a structural ruleset can be checked in as early as RIBA stages 1-2 because all the structural design elements are finalised at this stage. Comparatively, a ruleset concerned with medical equipment can only be checked after stage 5 and requires a LOD400 or more to have all the required information about the purchased and installed medical equipment in the BIM model.

3.2.3. Performing the automated check of the rules

Most of the studies in this stream took a specific code or regulation as a case study, for example, Liu et al. (2014) investigated an automated code checking for HVAC building code, while Zhang et al. (2013) applied it in the context of health and safety regulations. Martins and Monteiro (2013) developed an automated system in the context of the regulations of water distribution systems in buildings. These studies although have made a considerable effort to check a certain requirement but to date, there is very limited work done in creating a full model for automating healthcare facility codes using BIM models that are considering all the building regulations concerned with healthcare buildings.

3.3. CORENET

CORENET stands for (COnstruction and RealEstate Network), it is a government initiative by the Ministry of National Development in Singapore that started in 1995, and it is managed by the Building and Construction Authority. It represents the earliest code checking effort at a government level. The CORENET platform (http://www.corenet.gov.sg/) has three main parts: e-Submission that is used to follow up in building permits, e-Info guides different building stakeholders and e-PlanCheck that is concerned with automated code compliance. e-PlanCheck has two main modules the building plans module called IBP, and it has automated checks for rules concerning fire safety regulations, environment and sustainability regulations, and access control, building management systems and parking. The other module is concerned with checking building services, and it is called (IBS) (Eastman et al., 2009). This module includes rules for an automated check of electrical, plumbing, fire alarms, HVAC, water systems and gas pipes. CORENET is considered the most mature system for automated, rule-based check that is done so far.

CORENET has a platform called FORNAX which is an object-based platform that uses IFC extensions and the definition of the rules that will be checked (Solihin, W, 2004). The most significant advantage of FORNAX platform is that it has the rules hardcoded in the platform, so that a programmer does not need to write a code to extract the IFC properties from the building code because FORNAX can understand the code written in natural language and translate it to the IFC property to check a specific building object. For the reporting of the check results, ePLanCheck has a website that can perform the check against the codes and report it in a PDF or HTML via the web browser, so a user does not need specific software to perform the test which is another advantage of the CORENET platform.

3.4. Solibri

Solibri is a commercial BIM model checking software that has several mechanisms and tools to check models. It includes a built-in set of rules based on building regulations and international standards such as fire codes and accessibility codes, the results of these checks can be presented visually or in a pdf or XML format file. An important feature that was added recently is that the platform enables users to edit the parametric value of built-in rules according to the standard used and even add additional rules based on the specific rules or requirements in the project at hand (Beach et al., 2013). One limitation of the platform is that the set of built-in rules are limited, and it covers only architecture design codes like accessibility, model elements, clash detection and ADA (American with Disability Act) compliance. However, to verify some of the complex client requirements in a healthcare facility, the rules must be created manually for each required check and uploaded to the software before the check can take place.

4. Proposed Automated Rule Based Code Checking model

Based on the review of literature and relevant work, and the problems identified in the process of capturing, assessing and automating requirements management, this section will introduce and analyse a new theoretical model that can be used in automating the process of requirement management in construction projects. The model namely Automated Rule-Based Code Compliance (ARBCC) consists of four main phases as shown in Fig 1:

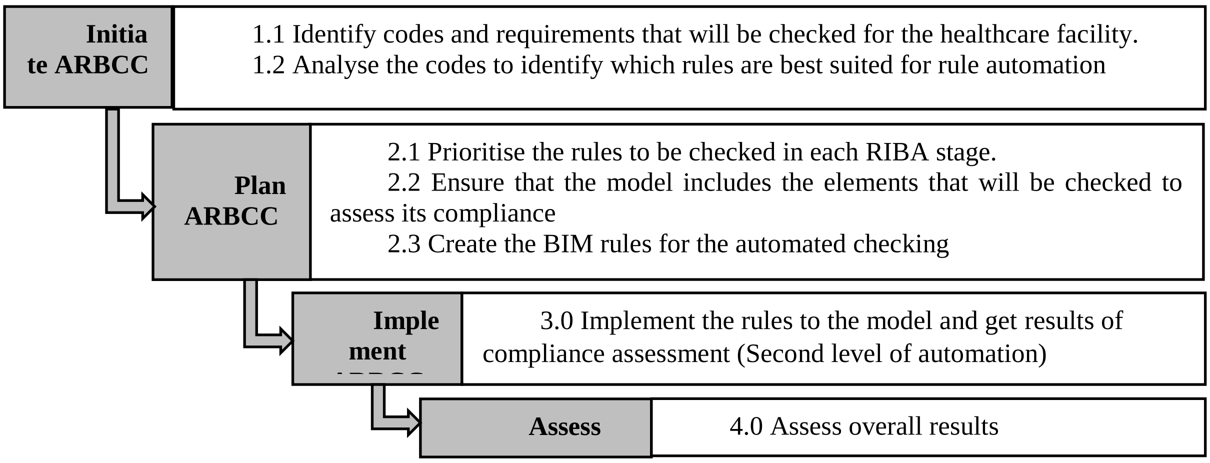


Fig 1: Automated Role Based Code Check (ARBCC) Process Model

4.1. Stage 1: Initiate Automated Code Compliance

One of the common shortfalls identified in the literature for automated code compliance is the lack of clarity and consensus on what codes should be automated. Some studies focus on certain regulation, some studies focus on checking building guidance, and others focus on local and international standards, that's why the process of initiating the ARBCC platform is important because it will give a clear and definite description of what codes/requirements will be checked and why they are important. This stage will involve two stages: identifying the applicable codes and regulations for healthcare facilities (Oystein, et al., 2009) and analysing these rules to ensure their compliance check process can be automated using Building Information modelling BIM.

4.1.1. Collate the healthcare codes and requirements

A healthcare facility has to comply with the UK building regulations because these regulations are mandatory to all types of buildings in the UK. There are 16 building regulations in the UK (Gov.uk, n.d.) as detailed in Table 1.

Table 1: UK building regulations

No.	Regulation Code	Subject
1	Document A	Structure
2	Document B	Fire safety
3	Document C	Site preparation and resistance to contaminates and moisture
4	Document D	Toxic substances
5	Document E	Resistance to sound
6	Document F	Ventilation
7	Document G	Sanitation, hot water safety and water efficiency
8	Document H	Drainage and waste disposal
9	Document J	Combustion appliances and fuel storage systems
10	Document K	Protection from falling, collision and impact
11	Document L	Conservation of fuel and power
12	Document M	Access to and use of buildings
13	Document P	Electrical safety
14	Document Q	Security in dwellings
15	Document R	High speed electronic communications networks
16	Document 7	Material and workmanship

Compliance with these regulations is mandatory not just for healthcare facilities but also for any building in the UK, that's why these regulations will be a good start point to any automated code compliance check system in the UK because it will cover all the mandatory aspects related to building systems and services

Furthermore, for the healthcare-specific regulations and guidance, the National Health Services (NHS) in the UK has a set of design guidance for healthcare buildings that are called Health Building Notes (HBN) (Gov.uk, n.d.). These notes can be analysed as a base for requirement check automation using BIM. The regulations cover two types of regulations, building regulations that illustrates requirements related to the spaces of healthcare buildings such as lifts, stairways, bathrooms…etc. The other type of regulations is related to the design of specific healthcare functional space such as pharmacies, cardiac facilities, and critical care units. Table 2 provides a list of all the 29 HBN regulations.

Table 2: NHS's Health Building Notes

No.	Guidance Code	Subject
1	(HBN 00-01)	Designing health and community care buildings
2	(HBN 00-02)	Designing sanitary spaces like bathrooms
3	(HBN 00-03)	Designing generic clinical and clinical support spaces
4	(HBN 00-04)	Designing stairways, lifts and corridors in healthcare buildings
5	(HBN 00-07)	Resilience planning for NHS facilities
6	(HBN 00-08)	The efficient management of healthcare estates and facilities
7	(HBN 00-09)	Infection control in the built environment
8	(HBN 00-10)	Design for flooring, walls, ceilings, sanitary ware and windows
9	(HBN 01-01)	Designing and planning cardiac facilities
10	(HBN 02-01)	Cancer treatment facilities: planning and design
11	(HBN 03-01)	Adult mental health units: planning and design
12	(HBN 03-02)	Facilities for child and adolescent mental health services
13	(HBN 04-01)	Adult in-patient facilities: planning and design
14	(HBN 04-02)	Critical care units: planning and design
15	(HBN 6)	Designing facilities for diagnostic imaging
16	(HBN 07-01)	Satellite dialysis units: planning and design
17	(HBN 07-02)	Main renal unit: planning and design
18	(HBN 08-02)	Dementia-friendly health and social care environments
19	(HBN 09-02)	Maternity care facilities: planning and design
20	(HBN 09-03)	Neonatal units: planning and design
21	(HBN 10-02)	Facilities for day surgery units
22	(HBN 11-01)	Facilities for primary and community care services
23	(HBN 12)	Designing an out-patients department
24	(HBN 13)	Planning and design of sterile services departments
25	(HBN 14-01)	Designing pharmacy and radio pharmacy facilities
26	(HBN 15)	Planning and designing facilities for pathology services
27	(HBN 15-01)	Planning and designing accident and emergency departments
28	(HBN 23)	Designing hospital accommodation for children
29	(HBN 26)	Facilities for surgical procedures in acute general hospitals

The above two sets of regulations can form a good base for an automated platform of building codes and regulations for healthcare facilities in the UK. The next step in the framework is to analyse these codes and regulations and extract the rules that will form the base of the automated check.

4.1.2. Analyse the codes to identify which rules are best suited for rule automation

This phase of the initiation process is to analyse each code and guideline document to identify the rules that can be extracted from it and used for automated rule check using BIM. Rule extraction process in this stage can be manual, i.e. by reading the guidance and segmenting it into rules then transfer these rules into computer readable rule using the software. Or it can be automated extraction of rules using semantic web technology or machine learning algorithms that are used to extract rules from text. Every one of the two approaches to extracting the rules from the documents has pros and cons. In the case of manually written rules from regulatory documents, the main advantage of the process is that it will provide a clear, ready to use list of rules but obviously the process will be time-consuming, error-prone and will require extensive experience in many areas like design, building services, BIM and healthcare services (Sarel and Fernández-Solis, 2010). On the other hand, automating the process of rule extraction from documents is much faster, and less costly, but due to lack of maturity of the approaches and technologies used, the output may still need manual processing before being used for rule-based BIM checking.

Some of the requirements will not be possible to be automated for many reasons. This is because some requirements are qualitative and subjective and they are challenging to be transferred into a computer readable and checkable rule (Eastman et al., 2009). Also, some rules require human judgment and its compliance can't be checked using BIM models (Soliman Junior et al., 2019). Furthermore, some clauses will require a certain level of development that is very complicated to be achieved in the BIM model. Moreover, some rules require human judgement and can't be tested using without using human logic/reason to analyse. In these cases, a separate list of these requirements will be created and analysed to find ways to rewrite the requirements in a way that will be more suited with automation. The knowledge gained from this process of learning how to write requirements that are easier to be recognised and checked digitally will be invaluable for future codes and regulations writing.

4.2. Plan Automated Code Compliance

From the previous stage, a list of rules should be extracted from the codes and regulations documentation. However, these rules are not prioritised according to the stages of actual building design and construction (Kiviniemi et al., 2004). For example, in one document there will be rules about how space is organised in zones which is a piece of information that can be checked at RIBA stage 0-1. However, in the same document, there will be rules about the equipment and their specifications; this information is not available in the BIM model before stage 5 when the equipment is procured. To streamline the process of the compliance check, the different extracted rules must be classified according to the RIBA stages. This classification will answer the question "when" these rules must be automatically checked using the BIM model. Once the rules are prioritised, it can then be added in the software that will cross check it with the project BIM model (Zhang & El-Gohary, 2012). On the other hand, the lessons learned from the analysis of the text documents of the different regulations and the rules extracted from it can be used to inform future development of regulations, and specifically how to write the regulations in a machine-readable language that is easier to be automatically checked using computer software.

For the BIM model, this analysis can inform what level of development is required in the BIM model and for each asset in different RIBA stage (Alnaggar and Pitt, 2018) to allow for the automated check of the rules, and also the IFC attributes that needs to be included in the model. This can be achieved by analysing each rule extracted from the regulation documents, and assigning specific data that needs to be included in the model to allow the check of the specific rule. For example, a safety rule that requires the material of the floor in the corridors of a healthcare facility must be of a material that is not slippery. Analysis of this rule requires that the BIM model have information about the floor material in corridors areas. Similar to this example, the analysis of all the rules will provide a list of all LOD requirements in the BIM model. Finally, these requirements can be included as an appendix to a template asset information requirement (AIR) document that should be in place if the automated check is required. This AIR will make it clear for all stakeholders in the BIM supply chain about what information is required and why to allow for automated, rule-based check of the model.

4.3. Implement Automated Code Compliance

The output of the planning stage of ARBCC will have two parts:

- A list of all applicable rules that are extracted from the identified regulations for general buildings and healthcare-related codes and requirements.
- A List of the information requirements with its associated LOD that is required in the BIM model to enable the automated check of the regulation rules.

To implement this framework in a live project, it will require creating the extracted rules in a model compliance check software and applying the rules inside the software to check BIM model compliance. As mentioned earlier, Solibri Model Checker (SMC) or similar software can be used to achieve this stage of the model. This automated implementation of compliance check will have several benefits.

First, it will be much faster than checking compliance manually. It will require less effort from the designer, and it also does not require a high level of skills to implement (Pauwels et al., 2011). Furthermore, the quality of the check will be much higher than the manual check, and fewer check errors will be achieved.

4.4. Assess Automated Code Compliance

The assessment of the results out of the software will then provide insights about the design problems and non-compliance areas with the codes, regulations and requirements checked. Reporting these issues in all stages of building lifecycle will have significant advantages. First, it reduces rework and discovers design issues earlier in the project. It also decreases the cost and time associated with solving design issues because these issues are then solved in the model before it is implemented in the project.

5. Conclusion and future work

The process of requirements management for healthcare building projects is complex because it involves management of a large amount of information such as building codes, regulations and healthcare related guidelines. This information has to be managed across different stakeholders such as architects, design consultants, construction engineers, and facility managers. The process of manually checking these requirements across different phases of building lifecycle is costly, labour intensive, time-consuming, and error-prone. This paper proposed a theoretical model to automate compliance checking of healthcare building regulations namely ARBCC (Automated Rule-Based Compliance Checking). The model has four stages initiation, planning, implementation and assessment. The primary advantage of this model is that it conceptualises the automation of the process considering the three main parts of the code checking. First, identifying the relevant building codes and requirements and how to translate them into machine-readable rules. Second, specifying the Level of Development (LOD) for the BIM model to ensure the BIM model have the required information to allow for this checking. Third, using adequate rule-based checking software to check if the BIM model complies with the healthcare rules and regulations. The ARBCC model is based on the issues and previous work in different areas of automated code checking from the literature review. Further work is currently being undertaken to implement the model to a segment of healthcare documentation of NHS, to better assess its applicability and results. This work applies this process model in automating the code compliance checking using the Health Building Notes (HBN) by the UK NHS as a case study following design science research methodology to gauge its effectiveness and value in establishing the first digital platform for compliance checking of building codes and requirements in the UK construction industry. The ARBCC model is using a semi-automated approach because a specialist must manually check the regulations and translate them into rules to be checked by rule-based checking software. However, future research areas in compliance checking can use National Language Processing (NLP) and Machine-Learning algorithms to automatically extract the rules from the text documents of building code/regulations, and make the process fully automated.

Acknowledgements

This work is a part of the research project “Recommendations for automated checking of regulations and requirements management in healthcare design” funded by the Centre for Digital Built Britain, under Innovate UK grant number RG96233. The project is led by University of Huddersfield in collaboration with UCL.

References

Alnaggar, A. and Pitt, M. (2018) *"Towards a conceptual framework to manage BIM/COBie asset data using a standard project management methodology."* Journal of Facilities Management Vol. 17 Issue: 2, pp. (175-187) Online: Available at: https://doi.org/10.1108/JFM-03-2018-0015 Accessed (2 April, 2019)

Apm.org.uk (n.d.) *"Requirements Management"* Online: Available at: https://www.apm.org.uk/body-of-knowledge/delivery/scope-management/requirements-management/ Accessed (7 April, 2019)

Architecture.com (2013) *"RIBA plan of work"* Online: Available at: https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work Accessed (2 April, 2019)

Beach T., Kasim, T., Li, H., Nisbet, N. and Rezgui, Y. (2013) *"Towards Automated Compliance Checking in the Construction Industry."* Proceedings of International Conference for Database and Expert Systems Applications. DEXA 2013. pp. (366-380).

Bouchlaghem, M., Kimmance, G. and Anumba, J. (2004), *"Integrating product and process information in the construction sector"*, Industrial Management and Data Systems, Vol. 104 No. 3, pp. (218-233).

Brady, T. and Davies, A. (2010), *"From hero to hubris – reconsidering the project management of Heathrow's Terminal 5"*, International Journal of Project Management, Vol. 28 No. 2, pp. (151-157).

Cheng, C. P., Lau, G. T., & Law, K. H. (2007). *"Mapping regulations to industry-specific taxonomies."* Proceedings of the 11th international conference on artificial intelligence and law. ICAIL '07., pp. (59–63). New York, USA

Choi, J., Choi, J., and Kim, I. (2014) *"Development of BIM-based evacuation regulation checking system for high-rise and complex buildings"* Automation in construction Vol. 46 pp. (38–49).

Cysneiros, M. (2002) *"Requirements engineering in the health care domain"* Proceedings of IEEE Joint International Conference on Requirements Engineering, 2002, pp. (350-356)

Davis, M. and Zweig, S. (2000), *"Requirements management made easy"*, Project Management Network, Vol. 14 No. 12, pp. (61-63).

Doulabi, R. and Asnaashari, E. (2016). *"Identifying Success Factors of Healthcare Facility Construction Projects in Iran."* Procedia Engineering Vol. 164, pp. (409-415)

El Kharbili, M. (2012). *"Business process regulatory compliance management solution frameworks: A comparative evaluation."* Proceedings of the eighth Asia-Pacific conference on conceptual modelling. Vol. 130, pp. (23–32).

Elliot, S. (2011) *"Transdisciplinary perspectives on environmental sustainability: a resource base and framework for IT-enabled business transformation."* MIS Quarterly. Vol. 35, 1 pp. (197-236).

Fernie, S., Green, D. and Weller, J. (2003), *"Dilettantes, discipline and discourse: requirements management for construction"*, Engineering, Construction and Architectural Management, Vol. 10, No. 5, pp. (354-367).

Gov.uk (n.d.) *"The Approved Documents provide guidance on ways to meet the building regulations."* Online: available at: https://www.gov.uk/government/collections/approved-documents Accessed 15 March, 2019.

Gov.uk (n.d.) *"Department of Health (DH) – Health building notes."* Online: available at: https://www.gov.uk/government/collections/health-building-notes-core-elements Accessed 17 March, 2019.

Han, C. Kunz, J. Law, K. (1998) *"Client/server framework for on-line building code checking,"* Journal on Computing in Civil Engineering, ASCE Vol. 12 No. (4) pp. (181–194).

Hietanen, J. and Final, S. (2006) *"IFC model view definition format"* International Alliance for Interoperability2006.

Hjelseth, E. and Nisbet, N. (2010) *"Exploring semantic based model checking"* CIBW78 2010: Proceedings of the 27th CIBW78 Conference: Applications of IT in the AEC Industry.

Hjelseth, E. and Nisbet, N. (2011) *"Capturing normative constraints by use of the semantic mark-up (RASE) methodology"* CIBW78 2011: 28th Conference: Applications of IT in the AEC Industry.

Jallow, A., Demian, P., Baldwin, A. and Anumba, C. (2014) "An e*mpirical study of the complexity of requirements management in construction projects"* Engineering, Construction and Architectural Management Vol. 21, No. 5, 2014 pp. (505-531)

Soliman Junior, J., Baldauf, J., Tzortzopoulos, P., Formoso, C. and Kagioglou, M. (2019) *"The Role of Building Information Modelling on Assessing Healthcare Design"* Proceedings of World Building Congress 2019, The Hong Kong Polytechnic University, Hong Kong, China.

Kiviniemi, A., Fischer, M., Bazjanac, V. and Paulson, B. (2004), *"Requirements Management Interface to Building Product Models: Problem Definition and Research Issue"*, PREMISS: CIFE, Stanford University, Stanford, CA.

Lee, J. (2012) *"Strategies for Healthcare Facilities, Construction, and Real Estate Management."* Healthcare Financial Management Vol. 66, pp. (94-101)

Liebich, T., Adachi, Y., Forester, J., Hyvarinen, J., Karstila, K. and Wix, J. (2006) *"Industry Foundation Classes IFC2×3"* International Alliance for Interoperability.

Liu, B., Akinci, M., Bergés, J.H., and Garrett Jr. (2014) *"Domain-specific querying formalisms for retrieving information of HVAC systems"* Journal of Civil Engineering Vol. 28, No.1, pp. (40–49).

Lederer, L. (2010), *"The role of monitoring and shirking in information systems project management",* International Journal of Project Management, Vol. 28, No. 1, pp. (14-25).

Martins, J., and Monteiro, A. (2013) *"LicA: a BIM based automated code-checking application for water distribution systems"*, Automation in construction Vol. 29, pp. (12–23).

Matt, C., Hess, T. & Benlian, A. (2015) *"Digital Transformation Strategies"* Business Information Systems Engineering Vol. 57, Iss. 5 pp. (339–343)

Miah, S., Kerr, D., and Hellens, L. (2014) *"A collective artefact design of decision support systems: design science research perspective"*, Information Technology & People, Vol. 27 Issue: 3, pp. (259-279)

Nawari, N. (2011) *"Automating codes conformance in structural domain"*, ASCE International Workshop on Computing in Civil Engineering, Miami, Florida.

Oyegoke, A. (2011) *"The constructive research approach in project management research"*, International Journal of Managing Projects in Business, Vol. 4 Issue: 4, pp. (573-595)

Oystein, N., Inger, S. and Peter, K. (2009) *"Query-based requirements engineering for health care information systems: Examples and prospects"* Proceedings of the 2009 ICSE Workshop on software engineering in health care, pp. (62-72)

Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J., DeMeyer, R., Van deWalle, R. and Van Campenhout, J. (2011) *"A semantic rule checking environment for building performance checking"* Automation in construction Vol. 5 pp. (506–518).

Potts, K. (2008), *"Change in the quantity surveying profession"*, in Smyth, H. and Pryke, S. (Eds), Collaborative Relationships in Construction: Developing Frameworks and Networks, Wiley-Blackwell, Oxford, pp. (42-58).

Salama, D. and El-Gohary, N. (2011) *"Semantic modeling for automated compliance checking"*, 2011 ASCE International Workshop on Computer in Civil Engineering.

Sarel, L. and Fernández-Solis, J. (2010) *"Complex Healthcare Facility Management and Lean Construction."* HERD: Health Environments Research & Design Journal Vol. 3 No. 2: pp. (3-6).

Solihin, W. (2004) *"Lessons learned from experience of code-checking implementation in Singapore"* Online: available at: https://www.researchgate.net/publication/280599027_Lessons_learned_from_experience_of_code-checking_implementation_in_Singapore Accessed 24 March, 2019.

Solihin, W., and Eastman, C. (2015) *"Classification of rules for automated BIM rule checking development."* Automation in Construction Vol. 53, pp. (69-82).

Tesch, D., Kloppenborg, J. and Frolick, N. (2007), *"IT project risk factors: the project management professionals perspective"*, Journal of Computer Information Systems, Vol. 47 No. 4, pp. (61-69).

Yu, W., Shen, P. and Chan, W. (2005) *"An analytical review of the briefing practice in Hong Kong's construction industry"*, The International Journal of Construction Management, Vol. 5 No. 1, pp. (77-89). ISSN 1562-3599.

Zhang, J. and El-Gohary, N. (2012) *"Extraction of construction regulatory requirements from textual documents using natural language processing techniques"*, 2012 ASCE International Workshop on Computer in Civil Engineering. pp. (453–460).

Zhang, S., Teizer, J., Lee, J.K., Eastman, C. and Venugopal, M. (2013) *"Building information modelling (BIM) and safety: automatic safety checking of construction models and schedules"* Automation in construction Vol. 29 pp. (183–195).

Zhang, X. Bayulken, B. Skitmore, M. Lu, W. & Huisingh, D. (2018) *"Sustainable urban transformations towards smarter, healthier cities: Theories, agendas and pathways"* Journal of Cleaner Production. Vol. 173 pp. (1-10)

Zhong, B., Ding, L., Luo, H., Zhou, Y., Hu, Y., and Hu, H. (2012) *"Ontology-based semantic modelling of regulation constraint for automated construction quality compliance checking"*, Automation in construction Vol. 28 pp. (58–70).

Optimizing Energy with Machine Learning Grey-Box Models

Sara Gilani[1], Elizabeth LeRiche[1], J.J. McArthur[1, *], Pierre Duez[2], Amin Omidvar[2] and Aijun An[2],
[1] Department of Architectural Science, Ryerson University
[2] Department of Electrical Engineering and Computer Science, York University
* email: jjmcarthur@ryerson.ca

Abstract

Model Predictive Control (MPC) has demonstrated great potential to improve the energy efficiency of buildings. However, using MPC traditionally requires a comprehensive knowledge of building construction to create dynamic models of buildings' zones and energy systems. This research presents a hybrid modeling approach as an alternative method. To this end, two and a half months' worth of data collected in a living lab test cell was used to develop black-box and grey-box models to characterize zone-level thermal response and optimize its temperature setpoints. The simulation results emphasized the necessity of considering flexible schedules and temperature setpoints based on occupancy, weather, and zone-level thermal response over a prediction window rather than standard fixed schedules and temperature setpoints. Moreover, the proposed hybrid modeling approach can be used for model-based predictive control in operating existing buildings.

Keywords: Experiment; Modeling; Simulation; Artificial neural network; Genetic algorithm.

1. Introduction

In recent years, there has been a considerable movement in improving the energy efficiency of heating, ventilation and air conditioning (HVAC) systems, as a significant proportion of building energy use is because of the HVAC systems (Pérez-Lombard, Ortiz, & Pout, 2008). Advanced control systems have emerged as effective ways in this regard. For instance, model predictive controls (MPCs) have demonstrated great potential to improve building systems' performance (Prívara, Váňa, Cigler, Oldewurtel, & Komárek, 2011; Oldewurtel et al., 2012). MPC in building energy management facilitates periodic adaptation of building systems to intermittent indoor (e.g. occupancy, electric equipment) and outdoor conditions (e.g. weather). Using a prediction window, MPC tackles the time lag in buildings' responses to intermittent conditions.

Achieving the benefits of MPC requires a dynamic model of buildings' zones and energy systems that best represents thermal responses of a zone and system. The three modeling approaches that can be used are white-box, grey-box, and black-box models (Li & Wen, 2014). White-box models (e.g. mathematical-physical models used in building performance simulation tools) are based on detailed modeling of a building and its systems. For instance, the lumped capacitance method is considered as a white-box model (Kramer, van Schijndel, & Schellen, 2012). Black-box models deal with the relationship between operational data where no knowledge about buildings' thermal properties is required (Harb, Boyanov, Hernandez, Streblow, & Müller, 2016). Grey-box models use both physical models and operational data (e.g. Jiménez, Madsen, & Andersen, 2008). Hence, implementation of white-box models in existing buildings requires a comprehensive set of as-built construction information. However, such information may not be easily available in existing buildings. In contrast, black-box and grey-box models can deal with this drawback of white-box models.

Previous research aimed at optimizing HVAC systems to reduce energy input and provide comfortable environment (Wang & Ma, 2008). MPC has been widely used to optimize HVAC system controls (Killian & Kozek, 2016). For instance, Corbin et al. (2013) incorporated a MPC environment that integrated a white-box model (using EnergyPlus) to optimize building control systems. The present research developed a hybrid model that combined grey-box with black-box modeling approaches to optimize the energy performance of a building system. Data collected over 2.5 months during the heating season in a full-scale living lab test cell was used to model thermal dynamics of the test cell as well as the HVAC system (i.e. heat pump) provided the heating demands of the test cell. Based on the developed grey-box and black-box models, the optimal control setpoints for MPC of the heat pump serving the test cell were identified to reduce heat pump's energy use while maintaining comfort conditions.

The test cell and collected data used to develop grey-box and black-box models are described in Section 2. Section 3 explains the methods of developing black-box models using artificial neural network (ANN), grey-box model, and the optimization process using multi-objective genetic algorithm (GA). Section 4 presents the simulation results and discussion of the results, followed by Section 5 which outlines the findings and limitations of the current study and necessary future work.

2. Description of the collected data

The data used for developing the black-box models were collected in an east-facing private office space in an academic building located on a dense urban campus in Toronto, Canada. The office test cell was a single faculty office adjacent to similar conditioned private offices to the north and south, and surrounded by a large student teaching space (above) and shared office (below). As the studied office was surrounded by other buildings, it received little direct solar radiation. A water-source heat pump delivered the heating and cooling demands of the office through a dedicated duct and adjacent offices on the same HVAC zone. A radiant heater also provided the heating demands to the office when the outdoor air temperature fell below 15˚C in the heating season. An air handling unit delivered tempered fresh air to the office through a dedicated outdoor air system with dedicated ductwork.

A local weather station on the roof of the building recorded outdoor air temperature and relative humidity, wind speed and direction, and solar radiation. The data collected in the test cell throughout the study were: occupancy, door position, use of lights and electric equipment, air temperature of the office, discharge air temperature and flow rate of the air handling unit and heat pump vents to the office. Table 1 presents a summary of the sensors used in the test cell to measure the aforementioned variables.

Table 1: Summary of the sensors used in the test cell.

Data collected	Sensor model	Description
Indoor air temperature	OmniSense S-10 Ambient Sensors	The sensors had an accuracy of ±0.4˚C with a resolution of 0.1˚C and data collection frequency of 5-6 minutes.
HVAC input	Wind Sensor Rev P data loggers	The sensors detected the velocity of the incoming air. The accuracy of the sensors was not provided by the vendor.
	AM2302 Temperature/humidity Sensor	The sensor was installed within the HVAC ducts leading to the test cell reading the temperature (with the accuracy of ±0.5˚C) and relative humidity (with the accuracy of ±2-5%) of the incoming air.
Occupancy	Toggle switch	The occupancy and light state of the test cell were recorded as occupants used the manual toggle switches.
Lights		
Door position	Reed switch	The reed switch installed on the door frame of the test cell opened and closed a circuit based on proximity to a magnet installed on the test cell's door.
Electrical equipment	Watts up? PRO	The power consumption of electric equipment was measured by a wattmeter at the power bar. The data logger was set to collect data at every 3 minutes.

3. Modeling and simulation

In this research, black-box models were developed to characterize a full-scale test cell's response to indoor and outdoor conditions. Using the developed black-box models, the thermal response of the test cell to varying inputs from the heat pump was simulated. This section presents the methodology used to develop black-box models followed by an explanation of the MATLAB-based simulation process to optimize the heating setpoints of the test cell.

3.1 Black-box and grey-box models

Prior to data modeling, the collected data from multiple data acquisition systems (i.e. sensors and weather station) from 22 November 2017 to 7 February 2018 were cleaned and organized. Due to the heterogeneity of the data, both in terms of type and sampling frequency, pre-preocessing was required to develop a coherent dataset. The collected data were averaged across each 5-minute timestep. However, for the occupancy, lights, and door states, the obtained averaged values were rounded to have an integer for these variables at each 5-minute timestep. Figure 1 presents the probability density of the outdoor air temperature and relative humidity as well as indoor air temperature measured in the test cell (T_{in}) during the data collection period. The relative frequency of the collected data indicates a wide range of indoor and outdoor conditions in the data collection period.

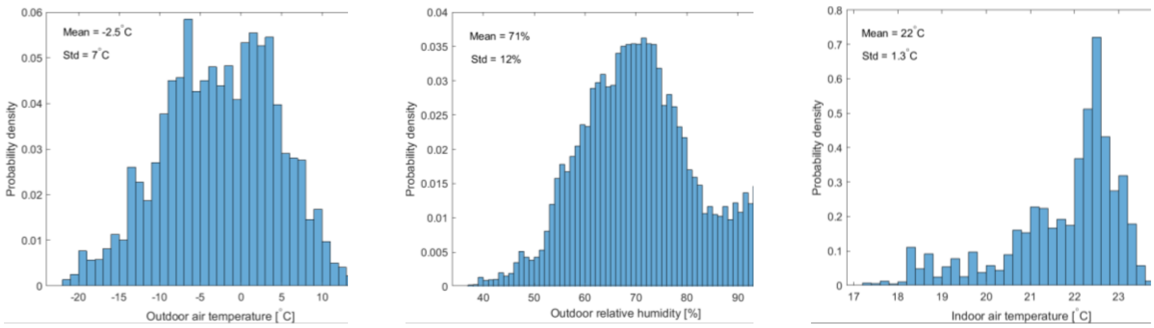


Figure 1: Probability densities of the indoor and outdoor conditions in the data collection period.

The distribution of the hourly occupied duration and the corresponding hourly occupied duration averaged across each hour on weekdays during the data collection period are shown in Figure 2. In general, the studied office had low occupied duration than standard occupancy schedules. It was occupied mostly between 9 am and 5 pm. In total, the office was occupied about 132 hours on weekdays during the data collection period. As shown in Figure 2, the test cell was mostly not occupied for the whole hour during business hours. There were a few days that the test cell was occupied for the whole hour during the data collection period.

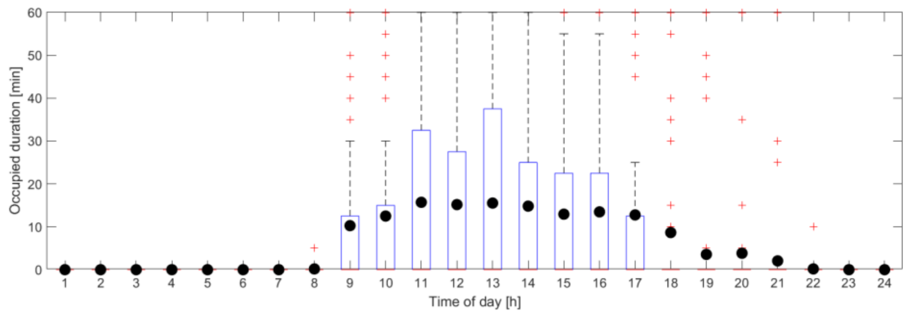


Figure 2: Distribution of hourly occupied duration (boxplot and outlier +'s) and mean hourly occupied duration (filled circles) on weekdays during the data collection period.

The collected data were used to develop black-box models to estimate the air temperature of the test cell. ANN method with one hidden layer was used to construct black-box models. The variety of the collected data facilitated training black-box models under different conditions. The input dataset and associated target outputs (i.e. indoor air temperature of the test cell) were used to train the ANN models in MATLAB. The ANN models were constructed with the 11 variables measured in the test cell, which resulted in the root mean squared error (RMSE) of about 0.6˚C in predicting the indoor air temperature. However, the input variables selected to train the ANN models were reduced afterwards. For instance, since the test cell was shaded by surrounding buildings, using solar radiation as input did not improve the accuracy of the models. Moreover, as there were relationships between occupancy and use of lights and electric equipment, adding lights and electric equipment use as input did not improve the accuracy of the models trained with the dataset included them. The input variables selected finally to train the ANN models included: outdoor air temperature, outdoor relative humidity, occupancy (i.e. number of occupants), door position, and air flow rate and temperature of the air handling unit and heat pump unit vents of the test cell. Using these variables resulted in the RMSE of about 0.6˚C.

Similar to previous research, different prediction windows were used to estimate building spaces' thermal behavior. For instance, Thomas and Soleimani-Mohseni (2007) stated that the minimum of 15-30 minutes as the prediction window in MPC in building controls is required. Mustafaraj et al.'s (2011) neural network-based models had a good performance in predicting air temperature of an open office within 30 minutes to three hours. Similarly, Ferracuti et al. (2017) showed the good performance of neural network-based models when the prediction window was shorter than three hours. In this research, to assess the performance of the ANN models, the models were constructed under varying prediction windows including 5, 30, 60, 90, 120, 150, and 180 minutes. For instance, for the prediction window of 30 minutes, an ANN model was developed using the input variables at each timestep to predict the air temperature of the test cell in the next 30 minutes.

To develop the ANN models for each of the considered prediction windows, the dataset was partitioned randomly using a stratified 10-fold cross-validation on the observations (i.e. 22464 data points). Note that as the order of the dataset was not arbitrary (it was time series), the dataset was not shuffled prior to splitting it into a training and test set. Each of the 10 partitions divided the data points into a training set and a test set. The 10-fold cross-validation partitioned the data points as 90% of the data points for training the ANN model and 10% of the data points for testing the corresponding developed ANN model. The RMSE of the indoor air temperature averaged across the 10 subsamples generated by the 10-fold cross-validation was almost identical (i.e. 0.6˚C) for the considered prediction windows. This error in short-term prediction of buildings' thermal behavior is in line with previous studies (e.g. Ferracuti et al., 2017). As an example, Figure 3 presents the measured air temperature versus the predicted air temperature of the test cell using the ANN models with the prediction window of 30 minutes for the training and test sets of the 10-fold cross-validation on the observations. The errors of the ANN models indicated the good performance of the models considering the wide range of the measured air temperature of the test cell during the data collection period.

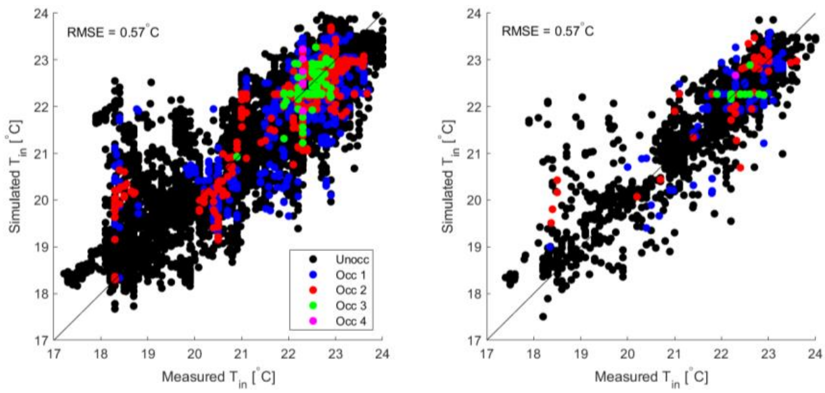


Figure 3: Five-minute time series of measured air temperature versus simulated air temperature of the test cell using the ANN model with the prediction window of 30 minutes on: (left) training set, and (right) test set.

3.2 Simulation process

This research formulated the optimal setpoint controls with two objectives: (1) reducing occupants' discomfort during occupied periods, and (2) reducing electricity energy use of the heat pump serving the test cell. This multi-objective optimization targeted the minimization of the vector of these two objectives.

In the simulation process, it was assumed that the test cell had a thermostat which was used to control the heat pump states (i.e. ON and OFF). The heating operation mode of the heat pump was set based on the test cell's temperature setpoint and air temperature. To find test cell's optimal setpoints for reducing electricity energy use of the heat pump while maintaining the test cell's temperature in the comfort zone (i.e. between 21˚C and 24˚C), various heating setpoints at varying prediction windows were tested. Table 2 presents the range of the considered heating setpoints in the optimization process. In total, the number of test cases were 14336.

Table 2: List of adjusted heating setpoints for each of the considered prediction windows (i.e. 5, 30, 60, 90, 120, 150, and 180 minutes).

Heating setpoint	**Minimum [˚C]**	**Maximum [˚C]**	**Increment [˚C]**
Occupied periods ($T_{sp,h,occ}$)	18	25	1
Unoccupied periods after the first arrival and before the last departure times on occupied days ($T_{sp,h,unocc,d}$)	10	25	
Unoccupied periods before the first arrival and after the last departure times on occupied days; and Unoccupied days ($T_{sp,h,unocc,n}$)	10	25	

Figure 4 presents a summary of the rule-based control strategy to find the optimal heating setpoints. For each test case of the heating setpoints, as the test cell's air temperature fell below the adjusted heating setpoint, the heat pump delivered the heating demand of the test cell; otherwise, the heat pump did not deliver any heating demands to the test cell. As shown in Figure 4, three variations of the heating setpoints were set: (1) on unoccupied days and occupied days before the first arrival time and after the last departure time ($T_{sp,h,unocc,n}$), (2) during unoccupied times after the first arrival time and last departure time on occupied days ($T_{sp,h,unocc,d}$), and (3) during occupied times on occupied days ($T_{sp,h,occ}$). In addition to the rule-based control strategy to optimize control setpoints, a baseline case was simulated. The control strategy for the baseline was on the basis of the standard practice in existing buildings. It was assumed that between 7am-7pm on weekdays, the heating setpoint was set to 21˚C. On weekends and before 7 am and after 7 pm on weekdays, the heating setpoint was set to 10˚C.

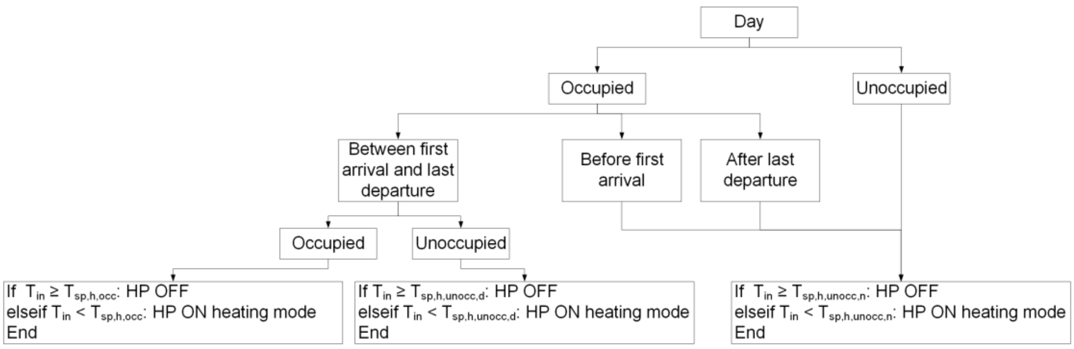


Figure 4: Rule-based control strategy to optimize temperature setpoints.

Optimizing control setpoints was based on the dataset which was used to construct the ANN models. Indoor and outdoor conditions were set to the measured data for each timestep (i.e. five minutes). However, the supply air temperature of the heat pump was calculated based on the air temperature of the test cell assuming the heat pump delivered the energy demands of the test cell at its maximum capacity and the return air vent was located in the test cell. A water-source heat pump model, which was almost identical to the one provided the heating and cooling demands of the test cell, was considered for the simulation process. The heating capacity of the considered heat pump was 5393 W, whereas its cooling capacity was 6887 W. Its energy efficiency ratio was 13.4 and the coefficient of performance was 4.4. The heat pump delivered an air flow rate of 0.3 m^3/s at the external static pressure of 0.20" (inches of water column). To avoid short cycling in the operation of the heat pump, it was assumed that it can slow down to a cruise control mode. The minimum air temperature supplied from the heat pump vent was set to be at the minimum of 10˚C lower than the air temperature of the test cell.

At each timestep, the air temperature of the test cell (T_{in}) was calculated using the black-box ANN models based on the inputs from the dataset, except for the air temperature and flow rate of the heat pump vent. Once the air temperature of the test cell was calculated, the air temperature and flow rate of the heat pump vent were calculated using the grey-box model (Figure 5) and the rule-based control strategy to optimize the control setpoints (see Figure 4). Note that the initial values of the air temperature and flow rate of the heat pump vent were assigned to be identical to the dataset. Moreover, as the heat pump delivered the energy demands of multiple rooms, the air flow rate from the heat pump vent to the test cell was calculated based on the average measured values.

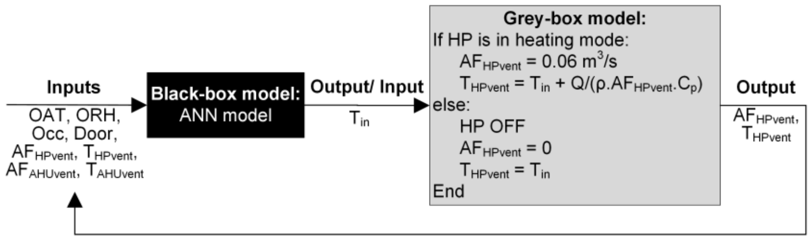


Figure 5: Inputs and outputs of black-box and grey-box models.

To find the optimal control setpoints among the considered ones, the multi-objective GA was implemented in MATLAB to find a set of points that have the relative minimal fitness function values (Pareto front) where reducing one fitness function (reducing electricity energy use) degraded another fitness function (increasing discomfort hours). The two fitness functions in the current research were to calculate: (1) the electricity energy use of the heat pump, and (2) the number of discomfort hours during occupied periods for the whole simulation time period. The multi-objective GA was set to create populations with 10 members per 10 generations. The sequence of generations was created based on the children type of mutation. Using the mutation children, single members of the population of a previous generation are randomly changed to form the population of the next generation.

4. Results and discussion

Table 3 presents the heating setpoints at Pareto front points obtained by the multi-objective GA. The obtained prediction windows for the optimal cases were 60 and 90 minutes. This prediction window means that for instance, the temperature setpoints of the test cell should be reset from the nighttime setbacks one hour before the occupant's first arrival time on an occupied day and one hour before the occupant left the office for the rest of that day. This trend is due to that the fixed temperature setpoints based on a standard occupancy schedule (between 7 am and 7 pm on weekdays) may not be applicable regarding flexible work schedules. For example, the occupancy profiles (see Figure 2) of the test cell shows that the office was in use mainly between 9 am and 5 pm during the data collection period. As such, the building spaces may be conditioned much earlier than when an occupant arrives an office or much longer than when an occupant leaves an office. Likewise, if an occupant arrives earlier than standard schedules or stays after standard schedules, the occupant will feel uncomfortable.

Determining optimal prediction window is also important in controlling HVAC system output as thermal response rates of buildings may not be as quick as what building operators assume in managing temperature setpoints. Hence, an occupant may feel uncomfortable when the occupant arrives an office. For instance, Dobbs and Hencey's (2014) study showed that controlling HVAC systems purely based on occupancy led to the reduction in energy use, however it increased occupants' discomfort upon their arrival to a space. Moreover, due to the delay in buildings' response because of their high thermal mass, it may take time to restore an office's temperature to a comfortable level once an occupant change the temperature setpoint or building operators adjust temperature setpoints following receiving occupants' complaints. However, accurate information of an existing building for developing white-box model of building thermal response may not be readily available. The current study used black-box models to predict thermal responses of the test cell to indoor and outdoor conditions without the requirement to go through detailed information of the thermal characteristics of the test cell.

In addition to the necessity of flexible schedules to reduce HVAC system output, the temperature setpoint values should also be revisited. For instance, in the current test cell, the optimal nighttime heating setpoints were 12-16˚C, rather than the commonly used temperature setbacks of 10˚C for the heating demands during weekends and nighttime on weekdays. Furthermore, the results of the studied test cell showed that on occupied days, the temperature setpoints should be adjusted during occupied and intermediate unoccupied periods, rather than determining fixed temperature setpoints (e.g. 21˚C for heating) for the whole business hours on weekdays. For instance, in this study, the optimization simulations yielded the optimal heating setpoint during occupied periods as 18-20˚C, whereas the optimal heating setpoint during unoccupied periods was 13-18˚C on the days that the occupant was present.

Table 3: Comparing Pareto front points with baseline.

Output \ **Case**		**Optimal cases**			**Baseline**
		1	2	3	
Prediction window [min]		60	60	90	5
Heating setpoint [˚C]	Occupied periods ($T_{sp,h,occ}$)	20	19	18	21
	Unoccupied periods after the first arrival and before the last departure times on occupied days ($T_{sp,h,unocc,d}$)	13	18	15	21
	Unoccupied periods before the first arrival and after the last departure times on occupied days; and Unoccupied days ($T_{sp,h,unocc,n}$)	16	13	12	10
Discomfort hours during occupied hours [h]		36	37	76	96
Electricity energy use [MJ]		824	221	21	2660

Figure 6 presents the average hourly air temperature of the test cell where the temperature setpoint was controlled based on the heating setpoints of the second optimal case compared to the baseline where the heating setpoints were adjusted based on the standard operating practice. These profiles show the hourly air temperature averaged across each hour during occupied periods, intermediate unoccupied periods, and unoccupied periods excluding intermediate unoccupied periods. Using the optimal heating setpoints, the average air temperature of the test cell was generally above 21˚C during occupied periods, whereas it was below 21˚C during occupied periods when the heating setpoint was controlled based on the standard practice in existing buildings. The simulation results showed that the fraction of occupied periods when the heat pump was on while the indoor temperature was below 21˚C reduced by 89% during occupied periods with the second optimal case compared to the baseline.

The mean hourly heating setpoints and occupied fraction on weekdays are displayed in Figure 7. As shown in this figure, the range of the average heating setpoint on the basis of the optimal heating setpoints of the second optimal case (see Table 3) was from 13˚C to 15˚C, while the fixed standard heating setpoints are 10˚C and 21˚C. During standard hours for resetting from setbacks, the average heating setpoint based on the optimal heating setpoints was lower than the fixed standard heating setpoint, whereas it was higher than the fixed standard heating setpoint during nighttime. This trend indicates that on average, using the optimal heating setpoints, the heating system provided more output during nighttime, whereas it provided less output during daytime compared to the fixed standard heating setpoints. Despite this trend, the heat pump electricity energy use and discomfort duration were lower with the optimal heating setpoints than the baseline (see Table 3).

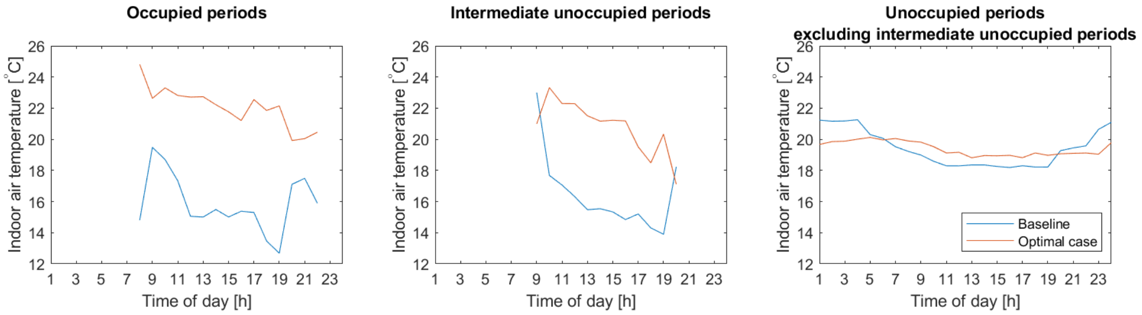


Figure 6: Mean hourly indoor air temperature of the optimal case #2 (see Table 3) and the baseline.

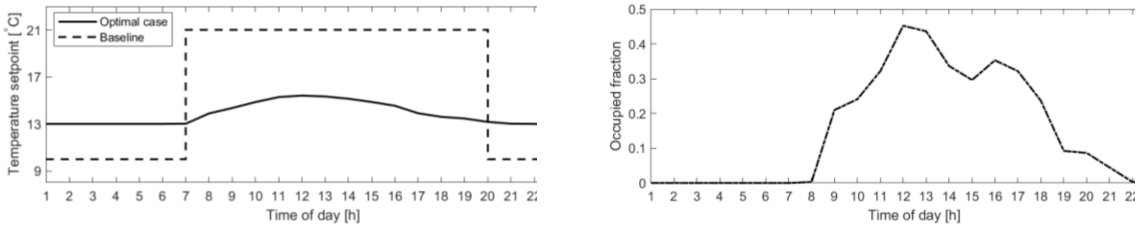


Figure 7: Comparing optimal case #2 (see Table 3) with baseline on weekdays: (left) simulated mean hourly heating temperature setback for the optimal case and baseline, (right) measured mean hourly occupied fraction.

This study showed that while fixed temperature setpoint schedules is a common practice in controlling HVAC systems, using a model predictive control and dynamic temperature setpoint control system based on occupancy, weather, and thermal response of the test cell can reduce energy use while keeping the air temperature of the test cell in the comfort zone. However, accurate prediction of occupancy, weather, and thermal responses of a building zone are necessary to control temperature setpoints properly. Moreover, the effectiveness of the proposed control system requires future real world data and testing in a living lab where full HVAC system control is possible.

5. Conclusions

This research combined black-box and grey-box models to develop a hybrid model to characterize thermal responses of a full-scale test cell without a requirement for a comprehensive knowledge of the physical characteristics of the test cell. Using the hybrid model, the temperature setpoints of the test cell for MPC of the heat pump delivered the heating demands of the test cell were optimized. The simulation results showed that flexible schedules and temperature setpoints based on occupancy, weather, and zone-level thermal response using MPC reduced energy use of the test cell compared to the standard practice in defining fixed schedules and temperature setpoints.

The method developed in the present research is an efficient method that can be applied in existing buildings where accurate as-built characteristics of a building space may not be readily available. Such black/grey-box model-based predictive control using real-time data can be used for continuous commissioning in existing buildings. This research had limitations that require future work. While this research used data-driven models for modeling the relationship between inputs and target outputs, the presented optimal temperature setpoints and control system were assessed using simulation. Further assessment of the control system necessitates a real test case. Generalization of the optimal control setpoints requires data collection in various cases studies. Moreover, future work on developing accurate models for predicting occupancy, weather, and thermal responses of the studied test cell is necessary.

Nomenclature

$AF_{AHUvent}$	Air flow rate of AHU vent (m3/s)	Q	Full capacity of HP in heating operation mode (W)
AF_{HPvent}	Air flow rate of HP vent (m3/s)	$T_{AHUvent}$	Air temperature of AHU vent (˚C)
AHU	Air handling unit	$T_{hallway}$	Air temperature of adjacent hallway (˚C)
C_p	Specific heat capacity of air (J/kg.K)	T_{HPvent}	Air temperature of HP vent (˚C)
Door	Door position	T_{in}	Indoor air temperature (˚C)
HP	Heat pump	$T_{sp,h,occ}$	Heating temperature setpoint during occupied hours (˚C)
OAT	Outdoor air temperature (˚C)	$T_{sp,h,unocc,d}$	Heating temperature setback during unoccupied hours on occupied days (˚C)
Occ	Number of occupants	$T_{sp,h,unocc,n}$	Heating temperature setback on unoccupied days (˚C)
ORH	Outdoor relative humidity (%)	ρ	Air density (kg/m^3)

Acknowledgements

This research was financially supported by the BRAIN Alliance - Big Data Research, Analytics, and Information Network, funded by the Ontario Research Fund Centres of Excellence program and FuseForward.

References

Corbin, C. D., Henze, G. P., & May-Ostendorp, P. (2013). A model predictive control optimization environment for real-time commercial building application. *Journal of Building Performance Simulation, 6*(3), 159–174.

Dobbs, J. R., & Hencey, B. M. (2014). Model predictive HVAC control with online occupancy model. *Energy and Buildings*, *82*, 675–684.

Ferracuti, F., Fonti, A., Ciabattoni, L., Pizzuti, S., Arteconi, A., Helsen, L., & Comodi, G. (2017). Data-driven models for short-term thermal behaviour prediction in real buildings. *Applied Energy, 204*, 1375–1387.

Harb, H., Boyanov, N., Hernandez, L., Streblow, R., & Müller, D. (2016). Development and validation of grey-box models for forecasting the thermal response of occupied buildings. *Energy and Buildings*, *117,* 199–207.

Jiménez, M. J., Madsen, H., & Andersen, K. K. (2008). Identification of the main thermal characteristics of building components using MATLAB. *Outdoor Testing, Analysis and Modelling of Building Components*, *43*(2), 170–180.

Killian, M., & Kozek, M. (2016). Ten questions concerning model predictive control for energy efficient buildings. *Building and Environment*, *105*, 403–412.

Kramer, R., van Schijndel, J., & Schellen, H. (2012). Simplified thermal and hygric building models: A literature review. *Frontiers of Architectural Research*, *1*(4), 318–325.

Li, X., & Wen, J. (2014). Review of building energy modeling for control and operation. *Renewable and Sustainable Energy Reviews*, *37*, 517–537.

Mustafaraj, G., Lowry, G., & Chen, J. (2011). Prediction of room temperature and relative humidity by autoregressive linear and nonlinear neural network models for an open office. *Energy and Buildings*, *43*(6), 1452–1460.

Oldewurtel, F., Parisio, A., Jones, C. N., Gyalistras, D., Gwerder, M., Stauch, V., … Morari, M. (2012). Use of model predictive control and weather forecasts for energy efficient building climate control. *Energy and Buildings*, *45*, 15–27.

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*, *40*(3), 394–398.

Prívara, S., Váňa, Z., Cigler, J., Oldewurtel, F., & Komárek, J. (2011). Role of MPC in Building Climate Control. In E. N. Pistikopoulos, M. C. Georgiadis, & A. C. Kokossis (Eds.), *Computer Aided Chemical Engineering* (Vol. 29, pp. 728–732). https://doi.org/10.1016/B978-0-444-53711-9.50146-2

Thomas, B., & Soleimani-Mohseni, M. (2007). Artificial neural network models for indoor temperature prediction: investigations in two buildings. *Neural Computing and Applications*, *16*(1), 81–89.

Wang, S., & Ma, Z. (2008). Supervisory and Optimal Control of Building HVAC Systems: A Review. *HVAC&R Research*, *14*(1), 3–32.

Centres of Excellence and Roadmaps for Digital Transition: Lessons for Ireland's Construction Industry.

Alan Hore[1*], Barry McAuley[2] and Roger West[3]

[1]School of Surveying and Construction Management, Technological University of Dublin, Bolton Street Campus, Dublin, Ireland.

[2]School of Multidisciplinary Technologies, Technological University of Dublin, Bolton Street Campus, Dublin, Ireland.

[3]Department of Civil, Structural Engineering and Environment Engineering, Trinity College, Dublin, Ireland

* email: alan.hore@dit.ie

Abstract

Like most sectors in today's working world, construction businesses are challenged to work in an increasingly digitised world with sophisticated demands from intelligent clients. So much has been written about the inefficiencies of the construction industry, its fragmentation, lack of collaboration, low margins, adversarial pricing, poor productivity, financial fragility, lack of research and development, poor industry image and relatively weak use of digital solutions. The Irish government recognises the importance of digital innovation to address many of the challenges the construction industry faces. With recent high profile reports of escalating spend on signature public sector projects and weak productivity performance in the sector, the Irish government is seeking out new strategies that will help create improved value for money for publically funded projects including stimulating economic growth and competitiveness in the sector. One such approach is the creation of a new Centre of Excellence for digital construction to help encourage both the government and industry to work together to create a more agile and innovation-rich sector, create jobs and improve project outcomes for public sector projects. In this paper, the authors will examine the current context surrounding this recommendation, in particular the vision of Ireland's National BIM Council to instigate the formation of a national central resource to support the rollout of digital tools and processes in Ireland. This paper serves mainly as a relatively high-level early desktop study that will document the missions and activities of particular international exemplars of such centres. The paper also seeks to potentially influence representative groupings in Ireland that have been charged with the responsibility of recommending to the Irish government the likely implementation model and funding mechanism that will help drive a sustained transformational programme for the Irish construction industry. The authors did not seek to consult with these stakeholders directly in preparation of this paper given the ongoing consultations at governmental level taking place in mid-2019.

Keywords : Digital, Excellence, Transformation, Ireland, BIM

1. Introduction

In 2017 the Irish government launched their strategy to increase the use of digital technology in key public works projects with Building Information Modelling (BIM) to be mandated in the design, construction and operation of public buildings and infrastructure over the next 4 years (GCCC, 2017). This statement of intent from the Irish government demonstrated an acute awareness of the importance of BIM and how it brings together technology, process improvements and digital information to radically improve project outcomes and asset operations. The industry reacted to this call for digital workflows and proposed, through a publication of the National BIM Council (NBC) of Ireland, a roadmap to digital transition for Ireland's construction industry from 2018 – 2021 (NBC, 2017). This industry roadmap is an initiative that advocates more productive ways of working that improves competitiveness at home and overseas. This roadmap not only seeks to increase efficiency and productivity in the industry but also aims to support an SME community that makes up almost 95% of the sector both in Ireland and across the broader European Union. The roadmap was divided into four key pillars; leadership, standards, education and training and procurement. One of the key recommendations within the leadership pillar in the roadmap was the establishment of a National BIM Centre of Excellence with a focus on driving the digital transformation of the sector. Such a resource can support the roll-out of digital tools and processes in Ireland while in the short term provides a platform for the digital transformation programme envisaged by the NBC in 2017.

A proposed centre has long been voiced in Ireland with Hore et al. outlining, as far back as 2011, their vision for a dedicated competence centre to facilitate the Irish construction industry (Hore et al., 2011).

The construction industry has responded to the requirement to keep pace with other sectors by its proposal for its own Digital Centre of Excellence. While the roadmap has been in circulation since late 2017, there has been no official announcement of its funding and formal implementation. To assist with the establishment of an Irish Digital Centre of Excellence, this paper will explore existing centres globally, to establish a possible framework that the Irish AEC Sector can follow once adequate funding becomes available.

The purpose of this paper is to undertake a scoping desktop exercise to be used in influencing any future proposal for a proposed Irish centre. The authors intend to extend this research at an appropriate time once the framework for such a centre has been established when those stakeholders charged with this responsibility have concluded their work. The authors contend that any proposed Irish entity will initially focus on BIM implementation support and the role out of the NBC roadmap. The centre, once established, should expand to focus on a broader spectrum of digital innovations.

It will be seen in the conclusion of this paper that the delivery of the NBC roadmap and any proposal for a newly established Centre of Excellence for Irish construction are extrinsically linked and connected projects.

2. Methodology

The methodology involved an initial high-level desk-top based research exploring existing international exemplars of such centres by primarily reviewing website content. Particular international centres were selected based on previous research by McAuley et al., (2018) and Hore et al., (2017a and 2017b) which recommended that Construction Scotland Innovation Centre and the Centre for Digital Built Britain be reviewed as potential best-case exemplars of such centres.

The authors do not intend to focus on the formal meaning of a Centre of Excellence but to locate international exemplars of communities of practices that focused primarily on the digitisation of construction. While it is expected that any future established entity will eventually focus on a more comprehensive range of digital construction innovations, the author’s key focus was placed on supporting the roll-out of Ireland’s BIM mandate, and, therefore, it is logical to limit the selection, at present, to those which are primarily focused within this area.

On that basis, the following centres were selected:

1. Centre for Digital Built Britain
2. Construction Scotland Innovation Centre
3. Global BIM Centre of Excellence China
4. NUS Centre of Excellence in BIM Integration Singapore
5. Australasian Joint Research Centre for BIM
6. The Digital Innovation Lab Georgia
7. Centre for Integrated Facilities at Stanford University

The authors focused on their mission/vision, governance, services offered, funding and a sample of their contributions.

3. Context

Project Ireland 2040 is the Government's long-term overarching strategy for Ireland (Government of Ireland, 2018a), which was further supported by a National Development Plan 2018-2027 (Government of Ireland, 2018b). The plan outlines how investment is made in public infrastructure in Ireland, moving away from the approach of the past, which saw public investment spread too thinly and investment decisions that did not align with a well-thought-out and defined strategy. Alongside the development of physical infrastructure, Project Ireland 2040 vision is to support businesses and communities across all of Ireland in realising their potential.

As part of this initiative, a Construction Sector Group (CSG) was formed to ensure that regular and open dialogue between government and industry takes place on how best to achieve and maintain a sustainable and innovative construction sector positioned to successfully deliver on the commitments in Project Ireland 2040. The CSG is made up of representatives of key industry bodies, as well as senior representatives of relevant government departments and agencies with responsibilities for policy and the delivery of infrastructure. Chaired by the Secretary General of the Department of Public Expenditure and Reform (DPER), the group reports to the Minister of the DPER.

The Project Ireland 2040 National Development Plan 2018-2027 outlined the key role of CSG (Government of Ireland, 2018b). Part of the group's remit will be to consider matters such as:

- the data/trends relating to the construction sector in Ireland;
- the supply of necessary skills and enhancing capacity;
- the role of Building Information Modelling and adopting other technologies and innovative practices in driving improved productivity and efficiencies;
- the use of sub-contracting and the level of self-employment and
- the productivity of the construction sector.

At the time of writing this paper, DPER, in collaboration with the CSG, has commissioned a study of the root causes of the poor productivity prevalent in the Irish construction industry together with potential Government policies and industry actions to tackle the root causes of this poor productivity (Government of Ireland, 2019). The Construction Industry Federation (CIF) recently published an important contextual report on the productivity of the Irish construction industry (CIF, 2019) which provided recommendations that were complementary to these tactics (CSG, 2019).

4. Digital Centre of Excellence Framework

This section will explore the seven selected international entities in more detail.

4.1 Mission

Dermol and Breznik (2012) describe a mission statement as an organisation's "credo," "philosophy," "core value," "reason for being," "image creator," or "a distinctive factor" as frequently used concepts that describe the importance and the value of an organisation. The majority of entities selected had multiple strategic goals.

The Centre for Digital Built Britain's mission is to "*develop and demonstrate policy and practical insights that will enable the exploitation of new and emerging technologies, data and analytics to enhance the natural and built environment, thereby driving up commercial competitiveness and productivity, as well as citizen quality of life and well-being*". This is expanded to "*act as the custodian of the integrity of the UK BIM, and Digital Built Britain Programmes across all the levels and to be recognised both nationally and internationally as that institution*". This is further advanced to include commitments to technical standards and protocols, acting as an academic bridgehead, tracking digital capabilities, inspiring the industrial community, adopting and implementing new digital approaches and ensuring that the findings and insights from the centre inform future policy, industrial practice, standards and research initiatives.

The Construction Scotland Innovation Centre vision *"is to uncover and develop with industry the value that lies in innovating and drive future demand for the innovation support available from Scotland's leading universities."* They also aim to empower industry, align academic expertise and public sector support, match industry needs to appropriate innovation support packages and deliver support from inception to commercialisation.

Other mission statements, such as that of the Global BIM Centre of Excellence, are not so task orientated and simply state that they aim to "*gather top BIM experts and excellent BIM enterprises both at home and abroad."*

The Centre of Excellence in BIM Integration in Singapore mission is *"to transform the way people design, deliver and manage the built environment through BIM innovation and practice."* This is expanded to include how this will be achieved, through high-impact research, broad-based education and collaboration with industry.

The Australasian Joint Research Centre for BIM focuses on developing leading research that integrates BIM with other advanced concepts and technologies to improve the performance and productivity of building projects in the energy, mineral and construction industries worldwide.

The Centre for Integrated Facilities' vision is to apply "*VDC principles and methods to help projects deliver exceptional value and help member organizations achieve breakthrough objectives in support of their exceptionally reliable design, engineering construction, and management to develop and operate sustainable facilitie*s."

The Digital Innovation Lab in Georgia aims to *connect industry to research, creating innovative ways to design, build, and operate buildings, cities, and infrastructure*.

Whilst not a mission per se, the NBC Roadmap envisaged that any new central resource established would '*support the rollout of digital tools and processes in Ireland. It will be a resource with both public and private commitment, which will leverage from existing digital interest communities'* (NBC Roadmap 2017, pp. 10).

4.2 Services Offered

The services offered by any organisation is ultimately the critical area of interest concerning the users. For the purposes of this paper, the authors focus primarily on BIM support services. The authors acknowledge that many of the centres selected have a remit beyond BIM and are now looking at a much broader ecosystem of digitalisation taking into account the impact of digital technologies, modern methods and broader innovative practices in construction.

The Centre for Digital Built Britain envisions a broad scope of commitments to support the adoption of BIM as business as usual and the evolution of the UK BIM Programme. They articulate the creation of a digital framework for infrastructure data through applied research including standards guidance, delivering pilots and outlining how the industry needs to change to establish how information-rich assets in the built environment can be planned and used to perform their functional service. They also generate informative publications, case studies, videos and blogs.

The Construction Scotland Innovation Centre offers skills programmes designed to support industry, educators, and learners. They also offer seminars, workshops, and conferences, providing a range of information suitable for all levels of BIM understanding. Also, they provide access to resources and industry experts.

The Global BIM Centre of Excellence aims to support BIM development by providing the latest BIM information, promoting industry communication, providing professional assessment, stimulating BIM application, accelerating BIM innovation and creation, and ultimately making contributions to BIM through sharing members' knowledge, techniques, experience, and opinions. The NUS Centre of Excellence in BIM Integration has two units. Their research unit focuses on developing leading research that improves building construction and performance through the integration of BIM with other advanced concepts and technologies. Their innovation and education unit focuses on developing guidelines, best practices, journals, etc. along with designing short term courses in BIM for the industry workforce.

The Australasian Joint Research Centre for BIM, through a series of pilot projects, aims to create and share knowledge to enhance policy development and enable key industry stakeholders to improve informed decision-making throughout a project's life cycle. The Digital Innovation Lab in Georgia provides a link that connects technology and professional members with real-world problems, while researchers try to provide emerging technology innovation and solutions to these problems. They have an annual symposium, member workshops, professional courses and a living laboratory that maintains a physical testbed for digitally integrated design, construction and operations projects. The Center for Integrated Facilities broadly covers a range of research areas. It is a mature research entity of international reputation working with industry to develop and test innovative ways to model and increase awareness of and competence in the use of the methods and to understand the value and costs of Virtual Design and Construction (VDC).

All of these entities have a central message that the construction industry is ripe for digital transformation and use a variety of tactics to drive this agenda within their network.

On further analysis of the services provided by these entities, there were three recurring pillars of activities, namely:

1. Research – systematic inquiry of particular studies or a particular problem of concern to industry. Many entities investigated included a resource of funded full-time and part-time investigators.
2. Education – provision of industry-led training, workshops, seminars, conferences, published papers, videos, webinars and case studies.
3. Guidance - publication of guidance material to assist industry in transitioning to BIM and other digital innovations.

4.3 Governance Models

The entities investigated had varying governance models. Table 1 provides a summary of the key stakeholders involved in each entity. A key feature was the hosting of such centres in Higher Education Institutes (HEIs).

Table 1: Stakeholders involved in selected entities

Entity	**Key Stakeholders**
Centre for Digital Built Britain	Department of Business, Energy & Industrial Strategy University of Cambridge (host)
Construction Scotland Innovation Centre	Scottish Funding Council Scottish Enterprise, Highlands & Islands Enterprise 14 Scottish university partners
Global BIM Centre of Excellence	University of Nottingham Ningbo Chartered Institution of Civil Engineering Surveyors China Member firms
NUS Centre of Excellence in BIM Integration	NUS Department of Architecture and the NUS Department Building (host) Real Estate Developers' Association of Singapore Member firms
Australasian Joint Research Centre for BIM	Curtin University (host) and Huazhong University of Science and Technology in Wuhan, China
The Digital Innovation Lab	Georgia Tech includes inter-department collaboration (host)
Centre for Integrated Facilities at Stanford University	Stanford University (Host) Member firms

All of the entities investigated appear to have strategic alliances with industry and parent governmental departments, which is a crucial element to any proposed strategic offering in Ireland.

A case in point is the Centre for Digital Built Britain in the UK where there is a strategic partnership between the UK government and the University of Cambridge. The Construction Scotland Innovation Centre differs in that it was an independent centre formed with links to government and multiple HEIs. The Scottish centre was only one of nine such centres in Scotland focusing on alternative industries.

The following alternative governance models were evident from this study of the seven entities selected.

- Model 1: Entity established in a single HEI with links to industry and government. These models tend to have a predominant research focus.
- Model 2: Entity establishes in two or more universities with links to industry and government. These models tend to have a predominant research focus with inter-institutional collaboration in specialist research areas.
- Model 3: Entity founded on a strategic partnership between government and academia with links to industry. These models tend to have a programme of activities that shape the strategic focus of the entity that includes the establishment of interest groupings, commissioning research, a dissemination programme that include hosting seminars, conferences, etc.
- Model 4: Entity established in an independent organisation with links to academia, industry, and government. These entities tend to be non-profit organisations.

4.4 Funding

Acknowledging the limitations of the desktop exercise, it is possible to deduce the funding mechanisms evident for each of the entities investigated

.

1. **Funding Model 1:** This model is focused on attracting research as part of a university's strategic research programme plan. The universities, in this case, compete for available funding to conduct high-impact research through research and development funding by a dedicated research resource of principal investigators and research students.
2. **Funding Model 2:** Funding, in this case, is provided by government and then acquired by a university that will work in partnership to deliver the requested R&D. The university is responsible for delivering the government's required BIM programme. An example of this is the Centre for Digital Built Britain who are funded, as part of the recommendations of the HM Government in the 2017 Autumn Budget, up to £5.4 million. This enables it to launch initiatives such as "Delivering a Digital Built Britain" which is a request for feasibility studies, research projects or experimental development projects ranging in value from £50,000 to £250,000.
3. **Funding Model 3:** Funding for this model is sought by an independent body outside of academia who receive funding by way of government or through industry. An example of this is the Construction Scotland Innovation Centre, which received almost £11 million of core funding to support the sector to innovate, modernise and grow from government funding. This funding can be then dispersed to universities or research bodies to do part of the required research, such as through Innovation Vouchers and collaborative innovation projects in which a percentage of overall project costs are provided from this source.

The above funding models offer alternative approaches and it seems likely that in an Irish centre would need significant state funding initially before it could become more reliant on alternative funding streams.

4.5 Sample Contributions

The paper thus far has investigated mission statements, services offered and funding models. While Section 4.2 investigated general services, this part of the paper will examine particular projects or contributions within each of the centres investigated. This will help to provide an understanding of the expected scope and type of projects envisaged for any new centre to be instigated for Ireland.

The Centre for Digital Built Britain has launched a “Research Bridgehead” which aims to build effective relationships with the research community to harness value, enabling results of innovative academic research to inform the development of Digital Built Britain. The bridgehead developed a network model that will bring together academic researchers, industry and stakeholder organisations to drive the creation of a digitally enabled landscape.

The centre is also establishing the “Digital Twin Hub,” a collaborative web-enabled community for those who own, or who are developing, digital twins within the built environment. They have published the first output of its “Digital Framework Task Group”, The Gemini Principles. The paper sets out proposed principles to guide the national digital twin repository and the information management framework that will enable it. They have also published the “Roadmap to the Information Management Framework for the Built Environment”.

The Construction Scotland Innovation Centre offers skills programmes designed to support industry, educators, and learners. The renewed “BIM in Practice” programme provides a unique opportunity to learn, collaborate and implement all things BIM. Working with the Scottish Funding Council, the centre part-funds the course fees of the students, who will also benefit from working closely with industry, contributing to industry research and helping participating businesses achieve higher levels of innovation and productivity. They also have a 3,500m^2 facility designed to support construction-related enterprises to collaborate and innovate.

Some of the research outputs from the NUS Centre of Excellence in BIM Integration include establishing an electronic Quick Bills of Quantities, safety risk drivers to assist with risk management and a BIM-based integrated workflow for the design of sustainable tall buildings. The Australasian Joint Research Centre for BIM has published more than 200 technical journal articles over the past five years and has presented innovative solutions to the oil and gas, mining and infrastructure sectors. Both the Digital Innovation Lab and Center for Integrated Facilities are renowned for their prodigious outputs and have been responsible for transformational changes, such as the National BIM Standard for Reinforced Concrete and pioneering research in the area of 4D BIM, respectively.

While some of the centres selected are more academically focused, this may not necessarily be the core focus of an Irish centre which could seek a more “applied” and pragmatic construction innovation programme where practical guidance and training is part of its core service model.

4.6 Proposed DCoE Framework

Based on the findings from this desktop-based research, the following framework is proposed to assist Ireland in the establishment of their Digital Centre of Excellence. The framework, illustrated in Figure 1, outlines the essential items that will need to be addressed, thus:

1. The mission statement should state the key areas outlined in Figure 1 and establish an initial scope of work.
2. The scope of work should be refined such that it dictates what area of expertise is required, such as, will the DCOE offer a research branch with innovation funding, etc., an education branch offering courses and workshops and a guidance branch offering consultancy through access to BIM experts?
3. The next stage involves the selection of a partner model that best represents the most advantageous way of achieving the agreed scope of services. While all partner models can be adapted to meet the range of services, some work better than others, for example, a DCOE established within a university would not be required to offer a guidance branch because it would not be expected that industry experts would be freely available to assist with BIM implementation.
4. Once an adequate mission statement, scope of services, areas of expertise and suitable partner model have been established, then one can identify what type of funding is required, whether governmental, industrial or a combination of both.

5. Finally, once funding has been secured, an achievable set of deliverables should be set, to maximise the impact.

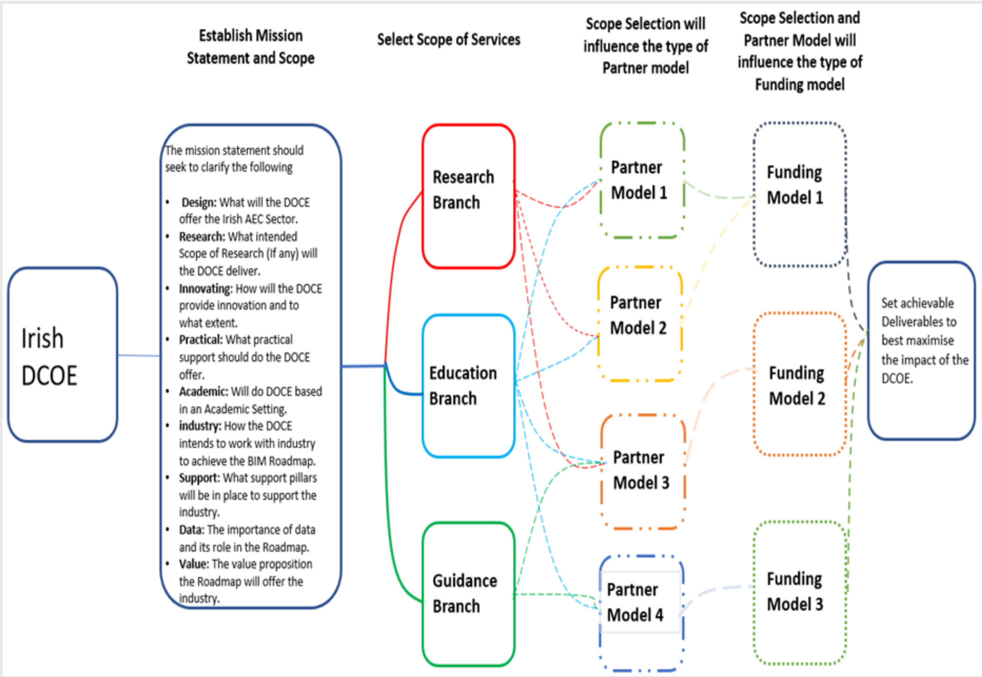


Figure 1: *Digital Centre of Excellence Framework*

5. Governance of DCoE

While the paper has established a proposed generic framework with different pathways, this section will explore how such an Irish focused Digital Centre of Excellence will potentially managed. Figure 2 illustrates how the authors envisage the governance framework for the newly proposed centre. At the core of the framework is the re-establishment of the NBC (Leadership Platform). It is recommended that a platform of the most knowledgeable persons represented by relevant stakeholders sits on this council and that a chairperson with appropriate credentials is appointed to lead this council.

It is recommended that the NBC will in turn report to the Project 2040 Steering Group via the Construction Sector Group who were established as part of the Project Ireland 2040 programme. It was stated earlier that the initial focus of the NBC would be the implementation of the NBC Roadmap for Digital Transition of Ireland's Construction industry. The NBC roadmap will need to be adapted to cater for the period 2019-2022.

In the author's opinion, the original remit and vision of the roadmap should be largely retained with the exception of the output from the recently commissioned construction productivity study by DPER, which should be included in an updated Roadmap.

It is recommended further that the Council include team leads for each of the four pillars outlined in the NBC Roadmap (leadership, standards, education and procurement). The authors believe it would be appropriate that the four-team leads are joined by a secretariat representative and progamme manager to make up the newly formed NBC Roadmap 2019-2022 Delivery Task Group who will be tasked with the delivery and roll out of the roadmap to support the Irish governments phased introduction of the public sector BIM mandate.

The core vision of the NBC will seek be to support the CSG remit of 1) securing the skills pipeline 2) driving productivity improvement in the Irish construction industry and 3) communication for industry confidence.

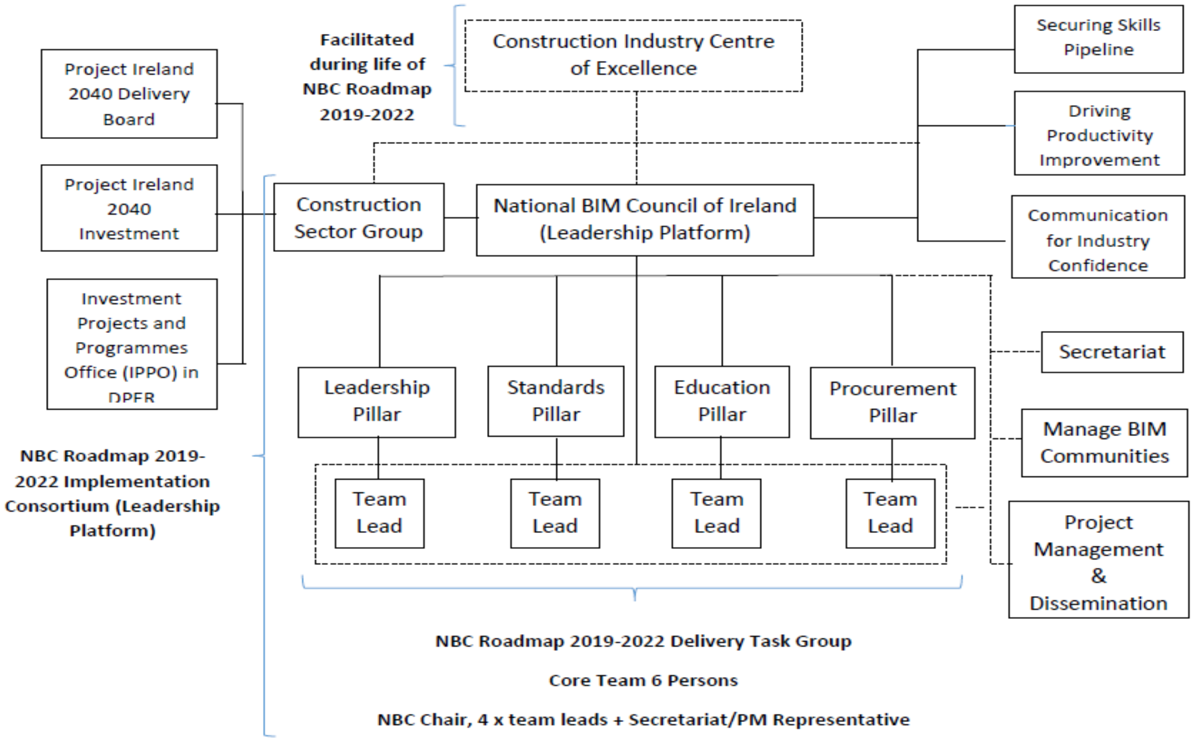


Figure 2: Proposed Framework for Newly Proposed Centre of Excellence (Hore A.V., 2019).

6. Recommendations

The paper has proposed two different frameworks; 1) a generic DCOE framework, and 2) Irish Digital Centre of Excellence Governance framework that will need to be considered in partnership. On this basis, the authors have made a series of recommendations that will require the two frameworks to be considered in unison, that is, a management framework will need to be agreed before a pathway can be established within the generic DCoE framework. Taking this into consideration, the authors recommend the following in respect to any newly established DCoE for Irish construction.

1. The first step should be the re-establishment of the NBC as a platform of leadership comprising of the most knowledgeable persons represented by relevant stakeholders and that a chairperson with appropriate credentials is appointed.
2. The NBC roadmap should be updated to reflect the recommendations from aspects of the DPER commissioned report on construction productivity believed to be completed in Q4 2019.
3. The NBC roadmap should be funded in advance of any decision to set up a new DCoE and that an NBC Roadmap 2019-2022 Delivery Task Group be appointed to support the rollout of the Irish government's public sector BIM mandate.
4. The leadership platform formed by the NBC should be the seed for the formation of a new CoE for Irish construction. It is essential that this platform consists of a strategic alliance between a parent government department and industry with academic input. A further more detailed study will be required prior to a preferred partnership model being suggested, before any final decision is made on the design and location of any new centre.
5. The Centre will need significant state funding initially before it could become more reliant on external alternative funding streams. Consideration should be given to the funding models in Figure 1 with a preference established once an agreed governance model is known.
6. Any new Centre envisaged should leverage the achievements of existing established communities focused on digital construction, for example, the Construction IT Alliance (CitA), and the CIF Construction 4.0 committee.

7. Conclusions

The Irish construction sector has experienced a return to productivity since the lows of the recession. To meet the requirements of an overworked and under skilled sector, as well as compensating for years of underfunding for infrastructure, the construction sector has embraced digital technologies, primarily BIM. This has resulted in the launch of a digital roadmap with a specific recommendation for a Digital Centre of Excellence. While funding has not yet been secured for such a centre, it was the purpose of the authors to investigate a potential framework that can be used to inform its design and implementation. An initial desktop-based research project exploring existing centres globally has determined that any future Irish Centre will need to follow international best practice. In the author's opinion, the original remit and vision of the roadmap should be primarily retained and implemented as soon as possible. This work will provide an essential backdrop for facilitating the formation of any newly proposed Centre of Excellence for Irish construction.

References

Construction Industry Federation (2019), An Examination of Productivity in the Irish Construction Industry, CIF Economic & Policy Research 2019.

Construction Sector Group (2019), Construction Centre of Excellence: A response by CSG industry members to the CSG Sub-Group on Growth & Productivity.

Dermol, V. and Breznik, K. (2012), "Identifying the mission statement's clusters in Slovenian economy," in Pastuszak, Z. (Ed.), Competencies, Synergy, and International Competitiveness Influence on the Technology Innovation and Industrial Management, Maria Sklodowska- Curie University, Lublin, pp. 798-806.

GCCC (2017), A Public Sector BIM Adoption Strategy, Ref CCP 01/17, 15th March 2017.

Government of Ireland, (2018a), Project Ireland 2040: Building Ireland's Future.

Government of Ireland, (2018b), Project Ireland 2040: National Development Plan 2018-2027.

Government of Ireland, (2019), Project Ireland 2040, Build Construction Sector Performance and Prospects 2019.

Hore, A., McAuley, B. and West, R. (2017a), Global BIM Study: Lessons for Ireland's BIM Programme, CitA Ltd.

Hore, A., McAuley, B. and West, R. (2017b), BIM in Ireland, CitA Ltd.

Hore, A., Montague, R., Thomas, K, Cullen, F., (2011), Advancing the use of BIM through a government-funded construction industry competency centre in Ireland, CIB W78 2011: 28th International Conference, Paris, 26-28 October 2011.

McAuley, B., Hore, A. and West, R., (2018), BIM Macro Adoption Study: Establishing Ireland's BIM Maturity and Managing Complex Change, International Journal of 3-D, Information Modeling, Iss 7, Volume 1, pp 1-11.

National BIM Council, (2017), Roadmap to Digital Transition for Ireland's Construction Industry, December 2017.

BIM and Lean Construction

LEAN HANDOVER™: DELIVERING COBIE DURING CONSTRUCTION

E. William East[1*] and John Ford[2]
[1] Director, Prairie Sky Consulting, Illinois, USA
[2] Digital Information Manager, Galliford-Try, Matlock, Derbyshire, UK
* email: bill.east@prairieskyconsulting.com

Abstract

The replacement of traditional construction handover deliverables with Construction Operations Building information exchange (COBie) complaint deliverables has not been going according to plan. The original COBie 2007 specification demonstrated that existing construction administration activities could be harnessed to capture COBie data with little to no technology support. In its current form, the COBie Standard is an Industry Foundation Class (IFC) Model View Definition (MVD) that has been almost exclusively adopted by the Building Information Modeling (BIM) community. While the COBie MVD normalized the original process-based data structure, the meaning derived from the construction administration process has been lost. This paper re-introduces the original motivation behind the COBie standard and describes a small case study demonstrating that incremental changes to existing construction administration process may ultimately lead to a new way of working. The benefits to this new way of working are evaluated from the point of view of Lean Construction, hence the effort has been branded Lean Handover™.

Keywords: COBie, Lean, Construction, Handover, NBIMS-US, BIM

1. Introduction

During the development of National Building Information Modeling Standard - United States ® Version 3 (NBIMS-US), the Technical Committee developed a set of criteria to differentiate “standards in fact” from those which were simply “standards in name.” The criteria used to evaluate NBIMS-US, V3 technical standards is show in Figure 1.

The first task in that process was to establish a clear business case. In fact, the question of the COBie business case arose well before COBie’s inclusion in NBIMS-US (East 2007). This question was not unexpected since similar questions had been asked of the first author during the development and implementation of information technology systems and standards over the previous four decades. Several approaches to answer this question were attempted, but these proved incomplete (East 2004) (East 2008) or too difficult to explain to practitioners (East 2009). Following the initial development and publication of COBie (East 2007), another approach, “value-added analysis,” was applied to construction administration with good result (East 2011). The essential insight of this new approach was to construct business process models at an “operational” level of detail to differentiate activities that added value versus those that did not. Seeing a way to tie-together the business process models required for the Information Delivery Manual directly to the potential benefits of process transformation, the 25 process models in the COBie standard were developed using the value-added approach (NIBS 2015). The power of the value-added approach to predict the potential effect of COBie-enabled business processes was demonstrated in the “COBie Calculator” (Fallon 2013). In addition to its use in the COBie standard, value-added analysis was also the basis for the Information Delivery Manuals for the Heating and Ventilating information exchange (HVACie), Water System information exchange (WSie), and the electrical system information exchange (Sparkie) standards published in the National BIM Standard - United States, Version 3® (NBIMS-US V3) (NIBS 2015) and the Building Automation Management information exchange (BAMie) specification.

The technical portion of each “information exchange” standard was used to “make standards” and included the Information Delivery Manual (Figure 1, Steps 1 and 2) and the Model View Definition (Step 3.a). To provide clearer picture for those who are unfamiliar with the STEP Physical File Format (SPFF), a spreadsheet mapping was also included in the COBie standard (Step 3.b). Unfortunately, many discussions about COBie do not pertain to COBie requirements (Steps 2.a thru 2c), but only to differences in mappings between the equivalent SPFF and spreadsheet format (Step 3.b).

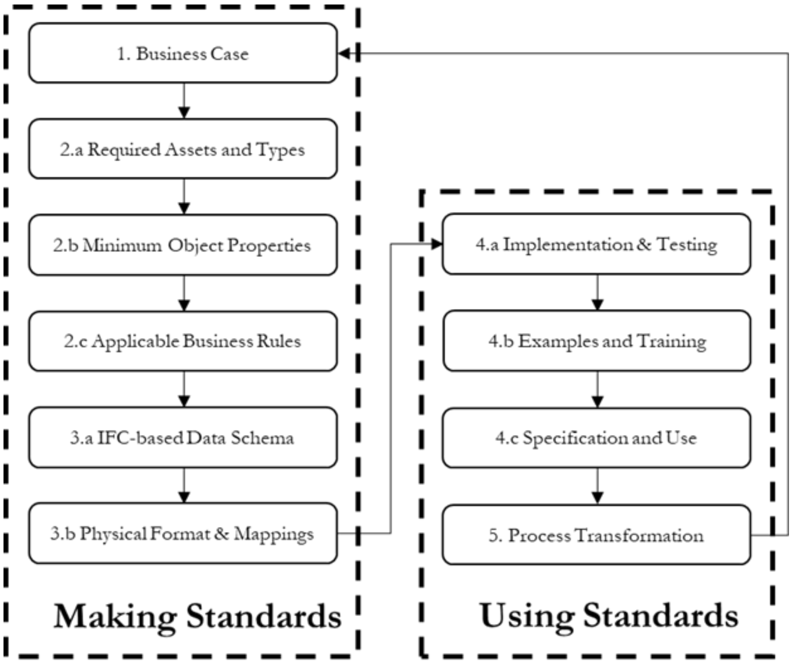


Figure 1. NBIMS-US V3 Information Exchange Standards

Beyond the technical aspects of the COBie standard, NBIMS-US V3 evidence of the use of the standards was also required. Documentation of commercial software implementation and testing (Step 4.a) against required business rules (Step 2.c) in any allowable format (Step 3a, 3b) was also required. Example files and training resources along with draft contract language supporting the “code,” “commentary,” and “specification” paradigm needed for physical construction deliverables were created (Step 4b and 4c). Through common understanding and implementation of the standard, process transformation (Step 5) was expected to validate the original COBie business case, allowing an ongoing process of innovation.

To date, the projects where the first author has directly engaged to help in capturing COBie data using the value-added approach described in the COBie business case (Figure 1, Step 1) have failed. In the view of the authors of this paper, the reason for that these failures is that those directly engaged with the production of COBie data are unaware of where, when, and who creates COBie data during the process of design and construction. As a result, the production of construction handover data (in COBie or any other format) remains unchanged from the traditional end-of-project data reproduction. The excuse for the ongoing use of traditional methods to create COBie data most often given to the authors of this paper is “we’ve just always done it that way.” The authors of this paper are not alone, in COBie implementations encountered in the literature we can see that the expected construction industry innovations have not occurred. For many, the examples of COBie data (WBDG 2010)(PSC 2017) in spreadsheet format and the need to pull-apart overloaded IFC 2x3 Coordination MVD SPFF files are the stopping point when thinking about COBie. As the inventor of the COBie standard, I find it ironic that the COBie spreadsheet, the aspect of COBie identified as “the most important reason for COBie’s success” by a representative of the largest US design software company, has also become a barrier to industry understanding and innovation.

2. Background

Prior to the formal publication of the COBie standard, Liu (2013) found that almost half of all Facility Management (FM) technicians had insufficient information to complete work orders. Even when FM staff participated earlier to include their requirements in the construction contract, the information provided was considered inadequate. A recent case study of the quality of construction handover data demonstrated that almost half of the handover information provided was incomplete or inaccurate and that collecting the information after construction was impossible due to physical obstruction or covering (Liu 2018). The most widely cited implementation of BIM (in the UK) attempted, as reported in Kelly (2013), to solve the construction handover problem by mandating that "BIM will provide a fully populated asset data set into CAFM Systems" with the aspiration that BIM use would increase accuracy and speed of information delivery and improve work order efficiency.

A question left unanswered in the UK mandate was noted in Volk (2014) to be the lack of objectively testable data quality standards. In 2015, however, the COBie standard proscribed a two-step COBie Quality Control (QC) process (NIBS 2015). The first step was to use pre-defined set of nine rules and "coverage" tables to verify that a data file conformed with COBie IDM's Exchange Requirement business rules. Free, open-source software automatically performs the verification testing (East 2016). The second COBie QC step was to validate that the information provided matched the information delivered on specific contract documents such as design schedules and construction submittals. Today, many continue to think that COBie deliverables must be customized for every project when, in fact, COBie data is objectively testable regardless of the specific project requirements.

Once owners began to include COBie data in contracts issues directly related to QC arose. The project identified in Pishada-Borzorgi (2018) encountered difficulties with the use and implementation of commercial software that claimed COBie compliance. Unfortunately, the conclusions drawn was not to properly QC deliverables using free software and enforce software's compliance with standard, but to hire "data wranglers" and incorporate proprietary software requirements. The authors of this paper, and many colleagues, have observed that COBie demonstrates our industry's willingness to pay double or triple the cost to partially fix something after the fact that could have been done once, correctly beforehand.

These difficulties are compound since the authors have first-hand experience, as do others (Kelly 2013), of the need to integrate construction handover data with multiple downstream information systems. One recent public owner organization encountered by the first author had different legacy maintenance, operations, asset management, and inventory control software in each of its three major facility portfolio divisions. The ability to achieve the UK proposed "BIMutopia" is further complicated by the reality imposed by the required life of building data when compared to that of the underlying contracts and technology (Miettinen 2014).

Of the case study papers reviewed, the one which reaches the heart of these problems used methodology derived from the field of sociology (Abdirad 2019). The primary conclusion reached in that paper was that contractors perceive COBie as a fixed deliverable requiring data management processes that conflict with the realities of a dynamic construction environment.

To address the complexity of construction handover, some authors have suggested adding new processes, software, and frameworks to capture COBie data (Florez 2018)(Matarneh 2018)(Alnagar 2019). Notably, Yalcinkaya (2019) suggests a visual interface to navigate COBie data that some readers will recognize as a "mind-map." As object-oriented data contains information in both relationships and objects, this abstract visualization is intuitively appealing. However, the root problem that COBie data is difficult to capture cannot be solved by layering on more software. We cannot continue to do "more of the same" and expect the outcome to be any different.

What is needed is an approach allowing project teams to capture COBie data as they work, creating, updating, and checking that data when it is captured and exchanged. In short a "Lean" approach. A comprehensive review of the application of BIM technologies to Lean Construction concludes that none of the Lean-BIM frameworks proposed in over 100 research publications can be practically implemented across the majority of construction companies (Tezel 2019).

3. Approach

To more clearly communicate how COBie implementation can lead to process transformation, the first author coined the term Lean Handover™. This objective of this phrase is to highlight the value-added benefits derived from an integrated COBie data collection method. This term also emphasizes that construction-phase COBie data is not created in BIM authoring software but in the construction administration processes documented in the original COBie report (East 2007) and listed below:

1. Identify submittal requirements
2. Define submittal schedule
3. Transmit submittal
4. Approve submittal
5. Install equipment
6. Commission equipment
7. Provide warranties
8. Provide spare parts sources
9. Transmit handover information

The book “Lean Handover™: COBie for Contractors” (East 2019) discusses the following topics: process-specific data mappings, procurement method variation, change processes, and delivery of real-time as-built project data. This book also describes the bench-testing of the approach by two Mechanical, Electrical, and Plumbing (MEP) subcontractors, one based in the US, the other in the UK. The project used for this testing was the “East Dormitory Project,” a publicly available set of lifecycle building data (Prairie 2017) based on a small two-story building. The first story of this building contains dining, recreational, and meeting spaces. The second story of this building contains single *en suite* bedrooms. In this paper, we introduce one portion of the effort described in the book, the portion pertaining to the definition, preparation, and transmission of construction submittals.

4. Traditional Submittal Processes

The selection of products occurs (at least) three times during a project: bidding stage, submittal stage, and purchasing stage. Our case study considered the “submittal stage” process. The construction submittal process has two primary variants. Value-added process maps for the Design-Bid-Build variant were first published in (East 2011). The Design-Bid-Build submittal process often begins with the designer creating a master “submittal register” whose contents are delivered by subcontractors to the prime contractor and owner’s representative for acknowledgement or approval. Subcontractors typically provide a single package of submittals for their entire set of specifications. Unless an extensive manual effort is undertaken, usually by the owner’s representative, to match the designer’s register with the contents of large subcontractor transmittal packages, most as-built submittal registers have little bearing with what was originally required by the designer. The matter is further complicated because the designer’s list of individual documents may not be provided by the selected product manufactures.

Under a Design-Build procurement, each subcontractor maintains a running register of what has been submitted. There is no issue with a mismatch between what is submitted and what is required, because the list is only of what has been submitted. This does, however, beg the question as to the quality of what was submitted. As a starting point in this case study we obtained examples of real Design-Build submittal packages for Design-Build projects. A cursory review of these documents identified missing, inconsistent, and duplicative information. The review had to be accomplished manually as manufacturer data was only available as images with fixed page numbering.

As was demonstrated in the first value-added analysis of a construction administration process, significant time and cost savings can be achieved shared structured submittal data when compared to posting or emailing documents (East 2011). While there are software vendors providing services to support the distribution of submittal documents using internet-based services, the authors are aware of no systems that has addressed the collection of associated COBie-required data from within submittal documents.

5. Lean Handover™ Submittal Processes

The most critical COBie-required construction handover data, manufacturer and model number, is created during the construction submittal process. In a document-centric submittal process, this information is found in PDF documents identified with manually added boxes or arrows. The information itself is only found by manual human interpretation. In the Lean Handover™ process, we capture COBie.Type.Manufacturer and COBie.Type.ModelNumber as part of the submittal process itself by making a slight change to the contractor's transmittal form. A portion of the overall COBie-based transmittal form for our case-study project's specification section "22 00 00 - PLUMBING, GENERAL PURPOSE" is shown in Figure 2. In our case study, we generated the complete set of all required submittal forms directly from the published East Dormitory design COBie file.

In the first column of Figure 2, is the list of COBie.Type(s) identified against the specific specification section. In columns two through five, the submitter provides the manufacturer, manufacturer's model number, supplier, and product data file name. The manufacturer and supplier names link to a form back-page requiring the entry COBie-compliant company information. In column five, the file name of the original manufacturer's product data sheet is provided. This file name can be copied and pasted to minimize data transcription errors. The product data file will also have boxes, arrows, and/or text comments to identify the selected model number. By copying and pasting the product model number directly from the PDF file, the COBie-based submittal form again minimizes transcription errors.

Name & Description	Manufacturer	Model Number	Supplier	Product Data
Bath Tub (Bath Tub_1675 mmx915 mm - Private)	Kohler	K-715	Champaign Lowe's	bath tub_K-715_spec.pdf
Lavatory - Vanity 1200 750m (Lavatory - Vanity 1200 750m_760 mmx455 mm - Private)	Corian - DuPont Corp	810	Champaign Lowe's	lavatory vanity_810.pdf
Lavatory-Vanity (Lavatory - Vanity_760 mmx455 mm - Private)	Elkay	EFU131610TC	Amazon	sink efu131610tc_spec.pdf
Lavatory-Wall Mounted (Lavatory - Wall Mounted_510 mmx455 mm - Public)	PickCompany	n/a	PickCompany	n/a
PLU-BallValveA (PLU-BallValve_15mm)	Milwaukee Valve	UPBA-475B 1/4"	Champaign Lowe's	valves UPBA475B.PDF

Figure 2 COBie-based Submittal Form (Part 1)

In addition to collecting manufacturer and model number when the product is first submitted, the fourth row of data in Figure 2 also highlights a quality control benefits of identifying product data before the product is installed. In the fourth row, the wall mounted lavatory product data file was not provided. Because the list of all COBie.Type(s) for each specification section is provided on the form, this omission is obvious to anyone visually scanning this information. The omission can be fixed, and the form resubmitted, rather than leaving the problem to a post-project data wrangler.

Of course, submittals for most products are not limited to product data files. Either by requirement or convention, files containing information related to testing reports, warranties, installation instructions, and operations and maintenance manuals may also be available and/or required to be provided. These files may be identified in that same COBie-based submittal form in Figure 1 with additional columns to the right of those pictured. In Figure 2, four additional documents type columns are shown. For our case we provided a fixed set of possible documents that may be provided, or not, depending on information available from the manufacturer. In the bathtub example, two separate files are provided. In the case of the vanity, submittal data of three different types is available in the same file.

Name & Description	Mfg Test	Mfg Warranty	Instructions	O&M
Bath Tub (Bath Tub_1675 mmx915 mm - Private)	n/a	Kohler_warranty.pdf	bath tub_K-715_install.pdf	n/a
Lavatory - Vanity 1200 750m (Lavatory - Vanity 1200 750m_760 mmx455 mm - Private)	n/a	n/a	n/a	n/a
Lavatory-Vanity (Lavatory - Vanity_760 mmx455 mm - Private)	n/a	sink efu131610tc_warranty.pdf	sink efu131610tc_install.pdf	sink efu131610tc_manual.pdf
Lavatory-Wall Mounted (Lavatory - Wall Mounted_510 mmx455 mm - Public)	n/a	n/a	n/a	n/a
PLU-BallValveA (PLU-BallValve_15mm)	n/a	n/a	n/a	n/a

Figure 3 COBie-based Submittal Form (Part 2)

While fixtures and other simple products can capture COBie-based submittals in a single row for each COBie.Type, some products are more complex. Such products will also have "accessory" products. It is not possible to specify these accessory products *a priori* since the details of each assembly are manufacturer dependent. As a result, a "pivot table" version of the COBie-based submittal form is also required, Figure 4.

The same basic information found in Figures 2 is also found at the top of Figure 4. However, the pivot submittal form lists additional documents (shown horizontally in Figure 3) vertically down the form. In the case the example Air Handling Unit, the manufacturer identifies twelve additional accessory products whose information (in this case) is provided in the product's data booklet (Figure 4).

Action:	Product Type:	Manufacturer	Model Number	Supplier
Initial	Air Handling Unit (Air Handling Unit_63300000 J)	VES Andover Ltd	MAX37/A/SW/S	VES Andover Ltd
Attached Data Files				
Product Data:	Air Handling Unit.pdf			
Mfg Test Report:	n/a			
Mfg Warranty:	Air Handling Unit Warranty.pdf			
Instructions:	Air Handling Unit Operation.pdf			
Maintenance Manual:	Air Handling Unit O&M.pdf			
Replacement Parts:	Air Handling Unit Warranty.pdf			
Field Test Reports:	n/a			
Accessory Products	**Accessory Name**	**Attached Data file**		
Product Data:	Fitted & Pre-Wired Isolator To Suit 1	Air Handling Unit.pdf		
Product Data:	24V Open Close Damper Motor	Air Handling Unit.pdf		
Product Data:	Filter Pressure Switch - Fitted	Air Handling Unit.pdf		
Product Data:	Magnehelic Gauge To Suit 0-250 Pa	Air Handling Unit.pdf		
Product Data:	Airflow Pressure Switch - Fitted	Air Handling Unit.pdf		
Product Data:	ELGN1050 Motor Isolator Supplied Fi	Air Handling Unit.pdf		
Product Data:	Filter Pressure Switch - Fitted	Air Handling Unit.pdf		
Product Data:	Magnehelic Gauge To Suit 0-250 Pa	Air Handling Unit.pdf		
Product Data:	Airflow Pressure Switch - Fitted	Air Handling Unit.pdf		
Product Data:	ELGN1050 Motor Isolator Supplied Fi	Air Handling Unit.pdf		
Product Data:	Fitted & Pre-Wired Isolator To Suit 1	Air Handling Unit.pdf		
Product Data:	24V Open Close Damper Motor	Air Handling Unit.pdf		

Figure 4 COBie-based Pivot Submittal Form

6. Observations

In this case study, two subcontractors were asked to download a set of simulated construction drawings. The scope of each subcontract was decided upon. Based on that scope the appropriate set of COBie-based submittal forms were provided to each subcontractor. Following a 15-minute introduction to these forms, the subcontractors completed the assigned forms. Observations made from written communications between the authors and case-study participants are described in the paragraphs below.

Initial discussion about the differences between US and UK construction were determined not to be differences in English-language dialects at all, but differences in assumptions related to Design-Bid-Build or Design-Build procurements. While the process of product selection in Design-Bid-Build projects is prescribed by tradition and contract requirements, the variety of “flavors” of Design-Build procurement methods, means that the creation of a set of submittal forms prior to construction may not be as helpful. Regardless of the specifics of the procurement, the responsibly to produce COBie-based submittal forms should fall to the design consultant (or subcontractor’s designer) who develops the construction documents (or shop-drawings). If needed, production of COBie-based submittal forms may be accomplished by the overall BIM Coordinator when each subcontract is signed.

Subcontractors in the US and UK found the COBie-based Submittal Forms were easy to understand and use because the forms were like those encountered on all other projects. This was a critical finding since the foundation of the Lean Handover™ approach is based upon the idea that small changes to existing methods may have profound effects. Subcontractors reported that they completed all forms in the same time required to prepare traditional submittals. The ultimate result of this observation is that providing COBie-based submittal forms, instead of pondering the apparent complexity of COBie spreadsheets, eliminates the need for project teams to hire COBie-specific resources or conduct post-construction surveys to recollect approved submittal information.

While the general use of COBie-based forms was understood, case study participants were less clear about the use of the forms in several important ways. First, the specific example forms provided did not support or enforce a complete set of COBie-compliant company contact data. As a result, full company details required by COBie did not always match the information provided by the subcontractors. Next, while the organization of products by specification section is consistent with traditional practice, there were situations where this was not completely satisfactory. For example, some specification sections included the delivery of general products that would have been purchased by multiple subcontractors. In some cases, the subcontractors suggested that product listings by product category might be relevant.

A third aspect of the COBie-based forms noted by the subcontractors was the need to reference the list of individual components when selecting products. While initially created COBie-based submittal forms included a linkage to show the individual COBie.Component(s) and spatial containment, these more detailed forms were not provided to the case-study participants specifically to determine if such information was required. Our study identified that such information may be helpful but would not be applicable to all types of products.

Our subcontractors recognized the internal value to capture equipment manufacturer and model number before building the project. Given subcontractor’s familiarity in working with PDF submittal documents, they were able to copy and paste file name and model numbers into the COBie-based Submittal forms for most products. We did not access the accuracy of manual data entry when only locked product data files were available.

The assumption that specification sections could be used as the basis for the pre-production of all COBie submittal forms from COBie.Type data was found most applicable to Design-Bid-Build projects. Depending on the “flavor” of Design-Build procurement, either a contractor-hired design team or a subcontractor-hired design team will be responsible for COBie.Type definition. As a result, the Lean Handover™ process must flexibly adapt to project-specific requirements

Although participating subcontractors have extensive experience using BIM software for construction coordination, they had not previously considered nor were concerned about the coordination of BIM and COBie data. This observation clearly speaks to the understanding, by subcontractors, that COBie data is not directly linked to current BIM processes in the construction trailer. It was also understood that unless the construction back-office data were captured in a way that allowed COBie data to be linked to BIM, that some owners might require them to manually re-type some of the COBie data within those BIM platforms.

7. Discussion

The transformation of small, corner groceries to the interconnected just-in-time business networks of Tesco and Walmart were not caused by client-facing technological innovation. The innovation we see today on a myriad of phone-apps are the affects, not the causes, of information technology innovation. Innovation in back-office processes led to the consolidation of retail and industrial sectors happened long before you could buy groceries on your phone. Today, the construction industry is awash in technology chasing users. It is awash in affects without causes. Demonstrations of user-facing technology shown to be wildly successful, are only so if the project has overheads to manually process and enter information across multiple systems. Such innovations cannot become mainstream. Each example use of the new technology requires another pilot project team to (ironically) prepare its own unique “Standard Operating Procedure.”

The only way to allow our industry to grow without mandating a “data wrangling” tax on every project is to fundamentally transform the systems that create back-office information. This paper demonstrated one of the most fundamental of these processes, is that of construction submittals. Rather than introduce new user-facing processes, terminology, and technology, the Lean Handover™ approach leverages existing processes, terminology, and technology. The small process changes made that seem second-nature to subcontractors after a 15-minute presentation will have a more profound and enabling effect upon innovation than our collective BIM aspirations. To prove that this claim is true we make the following predictions that can be validated by capturing information that can be directly coded as “type of work” on employee timecards.

Today, contractors, subcontractors, and facility operators must search for information by returning to the shop, gang box, or jobsite trailer. It was reported from a leading US university facility manager that a detailed audit indicated their operators had a “time on tools” value of 20%. Mechanics we know would rather work their trade than drive around looking for information or finding the necessary tool or part for six (6) hours a day. Unnecessary trips to the shop, gang box, or project trailer can be eliminated through the Lean Handover™ process.

Facility managers we have interviewed recognize that their parts inventory system is broken. This can be seen by multiple half-used boxes of the same type of part from different suppliers. With COBie data delivery of spare parts can be managed the same way as just in time delivery of parts for manufacturing lines. There is no need for each crew to have its own set of specialized tools, if the use of those tools can be tracked and shared. The wasted cost and accounting for parts and tools inventories can be eliminated through the Lean Handover™ process.

Today, there is no way to determine if construction administration or handover information is correct. This means that people, correctly, provide incomplete and incorrect handover data. Without a common way to assess what is required, it is not possible to understand when a job is completed. The wasted effort spent going back to complete partially finished handover data can be eliminated through the Lean Handover™ process.

Today, even when we attempt to use electronic file cabinets, the lack of underlying organization and version control for those documents means that multiple copies of virtually every document are kept by all parties with the resulting confusion. Knowing exactly what was approved, installed, and tested is only possible through a shared understanding of a common workflow. The wasted effort finding and moving duplicate versions of product data can be eliminated through the Lean Handover™ process.

Today, project teams wait until the fiscal completion of a building before preparing facility management data. Often this is months or years after the building has been occupied. In addition to having to recollect information that already exists, this delay typically means that product manufacturer warranties are voided since recommended maintenance activities were not completed by the contractor following prior to occupancy, or by the owner after occupancy. The wasted effort spent chasing and as-built and maintenance information can be eliminated through the Lean Handover™ process.

8. Conclusions

Owners know that traditional construction handover information is unusable. As a result, many large portfolio owners conduct post-occupancy surveys at a cost of millions of dollars per year. Owners are starting to demand a higher-quality construction handover product, but many are unclear exactly how to proceed. This case study demonstrates the most important of information - product manufacturer and model number - can be captured during the project eliminating cost of the post-construction job survey.

Today, contractors wait until the end of the project to send experienced staff or bespoke subcontractors to re-collect information known to subcontracting staff who selected and installed those products. There is international agreement that the tens or hundreds of thousands of dollars spent by contractors to produce document-based handover deliverables is wasted effort. The question for contractors and subcontractors is how to deliver faster, cheaper, and at higher quality products their competitors. This case study has demonstrated that the most important handover information can be captured regardless of the final output format required by the owner, COBie or not. While the full presentation of the Lean Handover™ approach is published in book form, the purpose of this paper was to identify issues where contractors and subcontractors expressed difficulty in adopting a single, generic approach to capturing part of the COBie data set in real-time. Those difficulties are to be expected given the fervor of those promoting BIMutopian visions when compared to the dynamic, yet enduring, need to capture construction information.

This case study, and work cited in this paper, should give pause to anyone who thinks that the development of a new process or software will be enough change the construction industry. This includes funding organizations, such as the Pankow Foundation, who considered development of steel and concrete MVD's to be the end-goal of their "standards" project. Despite the pedagogical interest in standards development, creating a standard is, in fact, the "easy" part of promoting industry change. It is one thing to create a data schema and even to mandate the delivery of standard data in contracts, but as the case of one of the most widely known MVD's, COBie, demonstrates, wishing does not make it so. If you build it, "they will not come." Changing our industry requires orders of magnitude more effort at a much different level of detail. An effort that requires testing and enforcement. An effort that demands working directly with those who create, use, and change project data.

The authors of this paper have been engaged in the application of computers in the construction office since they first arrived in the 1980's. In our view as much time has been spent by users of each round of "more efficient" technology arguing about outputs on paper or screens than has been spent talking about the subject project. This is the case because users with different backgrounds and experience have different expectations of what is to be accomplished. Without a common understanding of the system in which work is to take place, no effective agreement about the use of technology is possible. Rather than wait "five years" for the next round of emerging technology to be proposed as the next magic solution, we predict that construction information integration can only occur through the evolution of small changes to existing practice. The approach presented here is but a first step.

Acknowledgements

The authors wish to acknowledge the contribution of the following individuals and companies in the application of Lean Handover™ principles on the example East Dormitory project: Galliford Try, UK;

Gavin Dunstan, SES (Engineering Services), UK; and Alan DeLuce, Commercial Service of Bloomington, IN, USA. Lean Handover™ is a trademark of Prairie Sky Consulting®.

References

Abdirad, Hamid, Dossick, Carrie S. (2019) "Normative and descriptive models for COBie implementation: discrepancies and limitations", Engineering, Construction and Architectural Management, 26(6).

Alnaggar, Ahmed, Pitt, Michael (2019) "Towards a conceptual framework to manage BIM/COBie asset data using a standard project management methodology," Journal of Facilities Management, 17(2), pp.175-187.

East, E. William, Kirby, Jeffry G., Perez, Gonzalo (2004) “Improved Design Review through Web Collaboration,” Journal of Management in Engineering, American Society of Civil Engineers, 20(2), 51–55.

East, E. William, Kirby, Jeffry G., Liu, Liang Y. (2008) “Verification and Validation of a Project Collaboration Tool,” Automation in Construction, 17.2 (2008), 201-214.

East, E. William (2007) “Construction Operations Building Information Exchange (COBIE) Requirements Definition and Pilot Implementation Standard,” U.S. Army, Corps of Engineers, Engineer Research and Development Center, TR 07/30.

East, E. William, Martinez, Julio C., Kirby, Jeffrey G. (2009) “Discrete-Event Simulation-Based Performance Quantification of Web-Based and Traditional Bidder Inquiry Processes,” Automation in Construction, 18(2), 109-117.

East, E. William, Love, Danielle (2011) “Value-added Analysis of the Construction Submittal Process,” Automation in Construction, 20(2011), pp. 1070–1078.

East, E. William, Smith, Dana “Deke” Kennish (2016) “The United States National Building Information Modeling Standard: The First Decade,” Proceedings of the 2016 CIB W078 Conference, Brisbane, Australia, October 2016.

East, E. William, Bogen, Chris (2017) “Construction-Operations Building information exchange (COBie) Quality Control,” Prairie Sky Consulting, 2016, ISBN: 978-1-365-41018-5.

East, E. William, Ford, John (2019) “Lean Handover™: COBie for Contractors,” Prairie Sky Consulting, ISBN 978-0-359-61006-8.

Fallon, Kristine, Fadojutimi, Omobolawa, Williams, Gregory, Craford, Naila, Gran, Danielle, East, E. William (2013) “Assessment of Life Cycle Information Exchanges (LCie): Understanding the Value-Added Benefit of a COBie Process,” Engineer Research and Development Center, Contractor Report, ERDC/CERL CR-13-6.

Florez, Laura, Afsari, Kereshmeh (2018) “Integrated Facility Management Information into Building Information Modeling using COBie: Current Status and Future Directions,” Proceedings. of 35th International Symposium on Automation and Robotics in Construction

Hosseini, M. Reza, et.al (2018) “Integrating BIM into Facility Management: Typology Matrix of Information Handover Requirements,” International. Journal of Building Pathology and Adaptation, 36(1), pp. 2-14.

Kelly, Graham, et.al (2013) “BIM For Facility Management: A Review and Case Study Investigating the Value and Challenges,” Proceedings 13th International Conference. on Construction Applications of Virtual Reality.

Liu, Rui, Issa, Raja. (2013) “Issues in BIM for Facility Management from Industry Practitioners' Perspectives,” Proc. ASCE International Conference on Computing in Civil Engineering, pp. 411-418.

Lin, Yu-Cheng (2018) “Developing Final As-Built BIM Model Management System for Owners

During Project Closeout: A Case Study," Advanced Engineering Informatics, 26(2018), pp. 178-193.

Matarneh, Sandra, et.al. (2018) "Developing an Interoperability Framework for Building Information Models and Facility Management Systems," Proceedings of the Creative Construction Conference.

Miettinen, Reijo, Paavola, Sami (2014) "Beyond the BIM Utopia: Approaches to the Development and Implementation of Building Information Modeling," Automation in Construction, 43(2014), pp. 84-91.

NIBS (2015) "The National Building Information Model Standard - United States," buildingSMART alliance, National Institute of Building Sciences. COBie - Chapter 4.2 and Annexes.

Pishdad-Bozorgi, Pardis, et. al. (2018) "Planning and Developing Facility Management Enabled Building Information Model," Automation in Construction, 87, pp.22-38.

PSC (2017) "East Dormitory Test Files," Software Testing, Prairie Sky Consulting (https://www.prairieskyconsulting.com/testing.htm (cited 16-Nov-2018).

Tezel, Algan, et. al. (2019) "Lean Construction and BIM in Small and Medium-Sized Enterprises (SMEs) in Construction: A Systematic Literature Review," Canadian Journal of Civil Engineering, Vol 2019.

Volk, Rebekka, et.al (2014) "Building Information Modeling (BIM) for Existing Buildings - Literature Review and Future Needs," Automation in Construction, 38(2014), pp. 109-127.

WBDG (2010) "Common Building Information Model Files and Tools," Whole Building Design Guide, National Institute of Building Sciences (https://www.nibs.org/page/bsa_cobiemm (cited 28-Apr-2019).

Yalcinkaya, Mehmet, Singh, Vishal (2016) "Evaluating the Usability Aspects of COBie Standard," Proceedings of the CIB World Building Congress.

Yalcinkaya, Mehmet, Singh, Vishal (2019) "VisualCOBie for Facilities Management: A BIM Integrated, Visual Search and Information Management Platform for COBie Extension," Facilities, 37(7), pp.502-524.

The Last Planner System in view of Promise Theory

Mostafa Khanzadi[1, *], Mohammad M. Shahbazi[1], Farzad Pour Rahimian[2]
Moslem Sheikhkhoshkar[2]
[1] Iran University of Science and Technology, Tehran, Iran
[2]School of Science Engineering and Design, Teesside University, Middleborough, UK
* email: khanzadi@iust.ac.ir

Abstract

This paper aims at proposing a new insight into the context of construction management from the Promise Theory point of view. The theory advocates decentralization and forming a network of localized components, connected to each other in a chain of promises. Such method has been examined in configuration management systems, knowledge management and virtual organizations, with reportedly successful results. There are also footprints of such pattern in agile practices, especially in SCRUM method. However, little, if any, research has applied such a pattern in lean construction methods. Promise Theory point of view helps in a better understanding of how the agents can be separated, while linked in a self-organized manner in the context of lean methods in general and the Last Planner System in particular.

Keywords: Last Planner System, Promise Theory, SCRUM, Lean Construction, Agility.

1. Introduction

The main principle of lean methods is reducing wastes via reinforcing quality assignments and reliability of promises (Hamzeh, 2009). The Last Planner System (LPS), as a lean construction method, is not an exception. The significant difference between lean methods and traditional project planning methods, e.g. CPM, is that in the former, the actors, i.e. the “last planners” in the LPS are participated in decision making, whereas in the latter decisions are made in a centralized manner, often far from the settings in which the actions take place, both in terms of distance and time.

By the same token, agile strategies focus on thriving in unpredictable environments, e.g. IT management. In other words, to be agile, an enterprise or project must be structured appropriately to proactively and quickly adapt to change, seizing such opportunities to enhance value outcomes(Owen, Koskela, Henrich, & Codinhoto, 2006). SCRUM, as an agile method, has provided a new insight into managing highly variable and unpredictable environments (Kniberg & Skarin, 2010).

There are slight differences between LPS and SCRUM, in terms of leadership style. In fact, the former follows a sort of consultative-autocrat leadership style, that is the project leader absorbs the information input from the team members, though makes the ultimate decision (Odusami, Iyagba, & Omirin, 2003), whereas the latter relies on a flatter, self-managing, team-based structure rather than close, hierarchical management. In this sense, the scrum master is very much seen as a facilitator who tracks the progress of the team, allows them to make commitments to each other (Cervone, 2011), enables small, self-organizing teams to decide for themselves how they satisfy their value goals(Owen et al., 2006). The removal of tiered management effectively removes communications overhead, as well as minimizing system noises (Bonabeau & Meyer, 2001). This can be regarded as a paradigm shift in project management practices, since most project managers opt for following a well-prepared plan and the ensuing fight to get back on the plan when things go wrong. Adapting agile methods to construction management context requires significant changes in infrastructures and internal systems, especially in large organizations.

(Burgess, 2015b) proposes a novel viewpoint, Promise Theory (PT), in order to model the relationship between agents in decentralized decision-making systems. This paper argues that with a change in the point of view, construction managers could take the advantage of self-managing, though scalable teams. To this end, the PT and the underpinning theories and approaches are discussed.

2. Promise Theory

In philosophy, a promise is defined as a concept related to morality (Sheinman, 2011). In business, promises are not only about morality as imposed onto the promisor, but also contain valuable information for management of expectations. In this context, PT is regarded as a model of cooperation between autonomous agents, i.e. promisors and promises, who publish their intentions to one another in the form of promises (Charness & Dufwenberg, 2006). Carrillo and Dewatripont (Carrillo & Dewatripont, 2008) discussed that a promise can increase the likelihood of voluntary cooperation.

PT defines the promise as a scoped, documented intention that is exposed to another agent. It argues that a set of intentions is much more manageable than actions. In this sense, predictions and decisions are made based on the documented intentions each agent exposes to another. To this end, the conflict of intentions could be detected and resolved before turning into real issues. The theory emphasizes the following principles:

- Locality: avoid impositions, keep things close, and stay responsible.
- Reciprocity: nurture a repeated relationship, think of what drives the economic motor of agent relationships.
- Deal with uncertainties: have multiple contingencies for keeping promises. What will an agent do if a promise it relies on is not kept?

Fig. 1 shows how a promise flows throughout the agents. Agent A2 promises P (note the plus sign), with a promise body consisting of What, Where, When, and How (3W+H), to the agent A1. The agent A1 accepts (the negative sign denotes the acceptance) the promise with the details proposed by the agent A2.

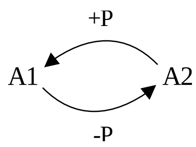


Fig. 1. The relation between agents in view of PT

Although the footprint of PT is meager in the context of management, it has been finding its way into the management arena in recent years. Burgess has introduced new insights into the field of knowledge management (Burgess, 2009). Shadi et al. (Shadi, Afsarmanesh, & Dastani, 2013) proposed a framework based on PT to model and monitor the behavior of agents in virtual organizations.

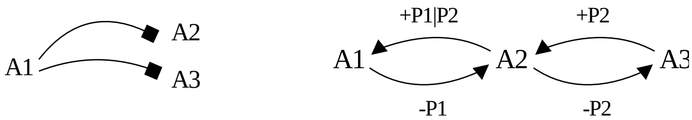
This research argues that the construction management context has come a long way from the command-control methods (e.g. CPM) to the pull methods (e.g. the LPS); the way is paved for a little more shift in viewpoint with a tendency to make construction environments even more collaborative and self-organized. The PT is likely the lever.

2.1. PT in construction

In traditional construction management methods (e.g. CPM), an obligation-/command-control (OCC) model was prevalent. Planning was done somewhere/sometime far from where/when the actions occurred. In this context, it is not surprising that construction practices deal with unpredicted situations that become increasingly unmanageable, leading to schedule pressure, erroneous outcomes, delays, and budget overruns. In addition, when the number of agents gets large, scalability would be a serious challenge in the case of imperative scripting and remote execution.

In recent years, lean methods revealed that project planning is not as easy as providing a CPM or Gantt chart. Construction projects, due to their complex nature and multiple layers of abstractions, require a novel approach for planning. Contrary to the traditional methods, the LPS suggests (1) approaching the planning to the implementation (in terms of time and space); (2) providing the team members with the opportunity to participate in decision making and planning processes.

In view of PT, the LPS upgrades the construction planning conventions via a number of drivers discussed in section 3. As shown in Fig. 2a, in OCC models, the commands often diverge from one person, i.e. usually the in-charge of the team (e.g. superintendent) to the other agents, whereas in PT model, there is a chain of promises convergent to one agent.



(a) (b)

Fig. 2. Task assignment in view of (a) OCC; (b) PT

This paper argues that, at the team level, the LPS follows neither OCC nor PT. It lies somewhere in between. The manager puts much effort to document the actions in the LPS board (Fig. 3) and assign the tasks to subordinates. Although it is a step forward, in the PT point of view, this is still a sort of managing actions rather than managing intentions.

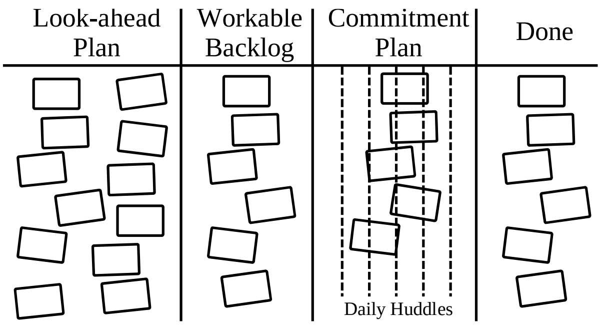


Fig. 3. The LPS board

To be more explicit about how the intentions are documented in the PT model, the following example explicates a scenario of pouring concrete in foundation F1. In this scenario, there are three agents: A1 (superintendent), A2 (concrete worker) and A3 (iron worker) and two promises P1 (pouring concrete) and P2 (reinforcement). The body of each promise is shown in Table 1.

Table 1. the body of promises

Promise	Promisor	Promise	What	Where	When
P1	A2	A1	poured-in concrete	F1	Tuesday
P2	A3	A2	reinforced foundation	F1	Thursday

According to Table 1 and Fig. 2b, the flow of promises is as follows:

1. The iron worker promises a reinforced F1 by Tuesday to the concrete worker (+P2).
2. The concrete worker accepts the iron worker's promise (-P2).
3. The concrete worker promises a poured-in, smoothed-over concrete by Thursday to the superintendent if the iron worker keeps his promise (+P1|P2).
4. The superintendent accepts the concrete worker's promise (-P1)

2.2. LPS in view of PT

At the weekly work plan level, task assignment procedure of the LPS can be justified in a PT way as follows:

1. In weekly meetings, the manager distinguishes the workable tasks, enlists them in "Workable Backlog".
2. The team members, intend to perform the tasks they can do based on their KSA (i.e. Knowledge, Skills, Abilities)
3. Intentions are documented.
4. The conditional intentions are identified and the promise network is formed and documented.

5. Cooperations are formed once the promises are accepted by the promises.

3. PT Drivers

Despite the wealth of recent works on the examination and applications of the LPS in construction project management, little work, if any, has studied the method from the PT point of view. The authors argue that digging into the intricate network of promises, intentions and the agents, helps to better understand and develop the principle of the LPS in particular and pull methods in general. For this, the following attempts to provide an insight into the drivers through which PT can empower LPS to make more difference via decentralization and mapping the set of workable backlogs to a chain of promises.

3.1. Dunbar’s limit

(Dunbar, 1992) suggested that there is a cognitive limit to the number of people with whom one can maintain stable social relationships—relationships in which an individual knows who each person is relates to every other person. Moreover, the more intimate relationships, the fewer we can maintain. In this sense, any strategy to reduce the number of connections and/or degrade the quality of connections would be of benefit to the manager. PT, advocates the flow of promises throughout a chain of agents rather than a divergent model of commands handed out by the manager. This shifts the effort from the unnecessary, delegable promises to the most critical ones.

3.2. Working memory

Working memory commonly refers to the cognitive process that enables individuals to maintain and process a limited amount of information at a time (Baddeley, 1992, 1998). Working memory plays a key role in occupational functioning. Although working memory can be rehearsed, it is limited (Cowan, 2010; Hogarth, 1987). The limitation does not allow us to link and process more than 3-5 issues at a time. To this end, delegating promises to subordinates frees up some slots (chunks) of memory for more substantial works.

3.3. Locality

In the conventional pull methods, from PT point of view, the team manager plays the role of a promise dealer. This violates a principle of PT, locality. According to locality, the greater the distance from the point of promise-making, the less causal responsibility an agent has in contributing to the outcome. Simply put, a promise, together with the necessary know-hows to assess and keep the promise, is preferably meant to be entirely localized in a single agent, so all the information required to discover inconsistencies, arising from conflicting promises, is automatically located in one place. In this sense, each agent is, by design, capable of resolving its own inconsistencies without any external help. This is a huge step forward for individual certainty (Burgess, 2015a).

3.4. Bounded rationality

Individuals' rationality in decision making is limited by the tractability of the decision problem, the cognitive limitations of their minds, and the time available to make the decision(Simon, 1972). Putting the PT together with game theoretic models in general and Nash's equilibrium model in particular, as well as the social exchange theory, reveals that cooperation is likely have explanations rooted in bounded rationality: Why should I keep my promises? What will I get out of it? The PT has the prospects to open new insights into modeling and understanding the relation between these themes.

3.5 Scalability

(Tainter, 1988) stated that as groups grow, tendencies would show up as specializing into different roles in order to scale up. However, separation comes at a cost: to get a service from a specialist, it is inevitable to reconnect with them. As agencies separate, they often form their own private languages that are not equilibrated with the general population, so there is a language barrier cost as well; bureaucracy and organizational silos get into the game. Eventually, due to the degradations in trusts, the cost of reconnecting through barriers will raise.

To this end, PT encourages decentralizing the flow of promises throughout the agents (i.e. specialists) that promise to know how to do their job. Decentralization in this manner, eases the bottlenecks that limit the enlargement. Decentralized, flat organizations exhibit scalability with less effort compared to the conventional hierarchical structures(Burgess, 2015b). The flourishing startups are the evidence for such statement. Google, as well, has shown tendencies and even movements towards flat organization structure.

3.6 Self-Determination Theory (SDT)

PT and SDT are both advocate of autonomy. Autonomy is, on the one hand, a presumption of the PT with the notion that "no agent can force any other agent to accept or transmit information, alter its state, or change its behavior. Also no agent may make a promise on behalf of any other"(Burgess, 2005, 2015b). On the other hand, autonomy is a human need from the SDT (Ryan & Deci, 2000).

PT, via encouraging to document the intentions rather than the actions, attempts to formulate outcomes by destination rather than getting deep into processes. In view of the SDT, this promotes the sense of autonomy and motivation among the agents.

4. Conclusions

This paper encourages a new insight into the LPS task assignment procedure from the PT point of view. In this view, decentralization is encouraged in order to promote the scalability and manageability of the team in a self-organized manner. In this sense, the team manager is more of a SCRUM master than of a CPM commander. Such a context has been examined in agile techniques, e.g. SCRUM, with reportedly successful outcomes.

However, applying such a viewpoint to construction management would not seem that easy. An issue that is expected to raise is that "Why they should keep their promises while there is no coercion?". Elaborate incentive mechanisms are deemed as helpful and necessary in motivating the individuals to keep their promises. The incentives could be contingent on the importance, urgency and the effort needed to keep the promise.

Moreover, establishing such a culture requires top managers to understand the full context of PT and create awareness about the principles of the theory in their subordinates.

Design management, due to the similarity to the IT context, seems promising as a start point for such a change.

References

Baddeley, A. (1992). Working memory. *Science, 255*(5044), 556-559.

Baddeley, A. (1998). Recent developments in working memory. *Current opinion in neurobiology, 8*(2), 234-238.

Bonabeau, E., & Meyer, C. (2001). Swarm intelligence: A whole new way to think about business. *Harvard business review, 79*(5), 106-115.

Burgess, M. (2005). *An approach to understanding policy based on autonomy and voluntary cooperation.* Paper presented at the International Workshop on Distributed Systems: Operations and Management.

Burgess, M. (2009). *Knowledge Management and Promises*, Berlin, Heidelberg.

Burgess, M. (2015a). *In Search of Certainty: the science of our information infrastructure*: " O'Reilly Media, Inc.".

Burgess, M. (2015b). *Thinking in promises: designing systems for cooperation*: " O'Reilly Media, Inc.".

Carrillo, J. D., & Dewatripont, M. (2008). Promises, promises,…. *The Economic Journal, 118*(531), 1453-1473.

Cervone, H. F. (2011). Understanding agile project management methods using Scrum. *OCLC Systems & Services: International digital library perspectives, 27*(1), 18-22.

Charness, G., & Dufwenberg, M. (2006). Promises and partnership. *Econometrica, 74*(6), 1579-1601.

Cowan, N. (2010). The magical mystery four: How is working memory capacity limited, and why? *Current directions in psychological science, 19*(1), 51-57.

Dunbar, R. I. (1992). Neocortex size as a constraint on group size in primates. *Journal of human evolution, 22*(6), 469-493.

Hamzeh, F. (2009). *Improving construction workflow-The role of production planning and* *control*. UC Berkeley,

Hogarth, R. M. (1987). *Judgement and choice: The psychology of decision*.

Kniberg, H., & Skarin, M. (2010). *Kanban and Scrum-making the most of both*: Lulu. com.

Odusami, K., Iyagba, R., & Omirin, M. (2003). The relationship between project leadership, team composition and construction project performance in Nigeria. *International journal of project management*, *21*(7), 519-527.

Owen, R., Koskela, L., Henrich, G., & Codinhoto, R. (2006). *Is agile project management applicable to construction?* Paper presented at the Proceedings of the 14th Annual Conference of the International Group for Lean Construction.

Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American psychologist, 55*(1), 68.

Shadi, M., Afsarmanesh, H., & Dastani, M. (2013). *Agent behaviour monitoring in virtual organizations.* Paper presented at the 2013 Workshops on Enabling Technologies: Infrastructure for Collaborative Enterprises.

Sheinman, H. (2011). *Promises and agreements: philosophical essays*: Oxford University Press.

Simon, H. A. (1972). Theories of bounded rationality. *Decision and organization*, *1*(1), 161-176.

Tainter, J. (1988). *The collapse of complex societies*: Cambridge university press.

Blockchain & Cyber-Physical Systems

Informing implementation of distributed ledger technology (DLT) in construction: interviews with industry and academia

Jennifer Li[1*] and Mohamad Kassem[1]
[1]Department of Mechanical & Construction Engineering, Faculty of Engineering & Environment, Northumbria University, Newcastle NE1 8ST, UK
* email: Jennifer.Li@northumbria.ac.uk

Abstract

This paper reports on the outcomes of seven semi-structured interviews that were conducted over a one-year period with industry practitioners and academics to discover the potential for distributed ledger technology (DLT) in the construction industry. Five themes were arose from the interviews: challenges for construction; smart contracts and payments; Building Information Modelling (BIM), collaboration and information sharing; the design development process; and regulations and compliance. Adversarial pricing, payments and poor regulations were identified as key challenges where DLT could support solutions. Smart contracts can lead to automation of activities in general, however, for payments, new financial legislation will need to be enacted beforehand. Smart contracts are unlikely to replace traditional construction contracts. Information is likely to be shared more freely leading to better collaboration for BIM-based projects. Recording of the design development process on a distributed ledger will provide the *who did what, when* that is currently lacking in construction projects and the operation of built assets. The immutable and transparent nature of DLT will hold people to account and encourage better compliance with regulations. Consideration needs to be given to: compliance with the General Data Protection Regulation (GDPR), how payments will account for the Construction Act, and to what extent smart contracts can be implemented in activities that require judgement on whether reasonable skill and care has been exercised. Future research will include further interviews and extension of a framework for implementation of DLT in the construction industry.

Keywords: distributed ledger technology (DLT), blockchain, construction industry, thematic analysis, smart contracts.

1. Introduction

Distributed ledger technology (DLT) is a way of recording transactions securely and in a decentralised manner. Many people refer to DLT as ‘blockchain’ which derived from *the Blockchain*, the specific technology that started the decentralised ledger revolution in 2009 with release of the world’s most prolific cryptocurrency, Bitcoin (Nakamoto, 2008). However, the Blockchain, an append-only chain of verified transactions (Dorri, Kanhere, Jurdak, & Gauravaram, 2017), is just one instance of DLT. Using the generalised term of blockchain in place of DLT, therefore, restricts its meaning to one type of DLT leaving out those such as IOTA’s Tangle which is a directed acyclic graph (Popov, 2018).

The construction industry is rife with challenges that do not appear to have been solved since the first major state of the construction industry report in 1994, the Latham Report (Latham, 1994). It has been followed by similar reports in the same vein such as the Egan Review (Egan, 1998), the Farmer Review (Farmer, 2016) and most recently the Hackitt Review (Hackitt, 2018). The key issues cited in these papers include low productivity, poor collaboration and information sharing, lack of enforcement of regulation and compliance, and poor payment practices.

Two major events took place in 2017 and 2018 that caused the United Kingdom’s (UK) Government to rethink its current construction industry practices. In June 2017, a breakdown in regulation and compliance caused a spark from an electrical appliance in Grenfell Tower, West London, a high-rise residential building, to spread to a building-wide fire killing 71 people (Symonds & Ellison, 2018). There were myriad failures throughout the building that did not meet safety standards with many claiming that building regulations were unclear (Booth & Davies, 2018). In 2018, the then UK's second largest construction contractor, Carillion, collapsed as a result of a broken procurement system and adversarial profit margins when it failed to pay its £1.5bn worth of debt having only £29m in the bank (Thomas, 2018).

DLT has been discussed as a tool to support many solutions to these challenges through its immutable, distributed, decentralised ledger (Jennifer Li, Greenwood, & Kassem, 2019). Some suggest DLT is a solution looking for a problem (Risius & Spohrer, 2017). The construction industry needs to be very careful not to implement the new innovation simply because it claims to be able to solve some of its challenges; a full and comprehensive review should be conducted looking at the requirements of implementing DLT in construction as well as considering alternatives (J. Li, Kassem, Ciribini, & Bolpagni, 2019). In addition, attention should be given to how these areas should be reformed and how cultural change within the industry is to be addressed. DLT is not a standalone solution; it is a tool that, when coupled with other tools such as Building Information Modelling (BIM), the Internet of Things (IoT) and smart contracts, has the potential to support digital transformation of the construction industry (J. Li et al., 2019).

The aim of this paper is to present findings from a series of interviews that were conducted with construction industry practitioners and academics with an interest in and knowledge of DLT to assimilate current thinking around the technology with regards prospects, potential use cases for construction and appetite for adoption. The research presented in this paper has informed to date a framework for achieving readiness to adopt DLT in the construction industry and is a continuation of this line of work (Jennifer Li et al., 2019). Section 2 describes the methodology adopted for this study; section 3 presents the findings from the interviews and provides a discussion; and section 4 concludes the paper and proposes next steps for the research.

2. Methodology

Following a comprehensive systematic literature review conducted by the authors in 2018 (Jennifer Li et al., 2019), a series of semi-structured interviews were conducted with seven people from across the construction industry. Due to the limited research that exists on DLT in construction, this qualitative research aimed to support the findings from the literature review and contribute further to the discussion of how the technology can address some of the industry's biggest challenges. The purpose of the interviews were to understand the perception and potential of DLT in construction and how it might integrate with other technological innovations in use today; questions were structured accordingly.

The criteria for selecting the participants were: senior experts from within the construction industry with an understanding of the industry's key challenges; experience of engaging with different types of organisations across the industry from contractors at all tiers to public sector clients; and knowledge and understanding of the potential for DLT in the industry. Table 1 shows the profile of the participants. To provide a holistic view of DLT across the UK's construction industry, participants were located across the UK from organisations ranging from micro-businesses to industry associations and large contractors. They were identified from within the authors' professional networks using a snowball sampling approach. The interviews took place over a one-year period as proprietary knowledge of the authors grew and as developments and interest across the industry increased in general.

A set of questions specific to DLT in general and smart contracts in particular were devised based on findings from the systematic literature review (Jennifer Li et al., 2019). Due to the novelty of the topic being investigated, the interviews were allowed to evolve throughout their duration to adapt to the participant's level of knowledge, expertise and interest in the subject, to provide flexibility to the process and avoid suppressing potential findings that would otherwise have remained undiscovered. Processing of the data followed the six-phase approach to thematic analysis as in Braun and Clarke (2012). First, each interview was transcribed; second, the data were coded based on initial analysis; third, the data were categorised into themes across all transcriptions capturing conceptual differences; fourth, the themes were quality checked against the data and revised based on deeper analysis; fifth, the themes were clearly defined; and six, the resulting categories were collated and interpreted for presentation in this paper to provide meaningful contributions to the field of DLT in construction.

Table 1: Profile of interview participants

ID	Role in the Construction Industry	Interview date	Duration
P1	Chief Executive of an industry association, barrister	Apr 2018	3hr 30m
P2	Head of construction and engineering in a national law firm	Nov 2018	50m
P3	Founder of a construction technology start-up utilising DLT	Dec 2018	2hr
P4	Senior Counsel of a global construction contractor	Dec 2018	30m
P5*	Professor in construction law at a Russel Group university	Dec 2018	1hr
P6*	Research Associate at a Russel Group university, architect	Dec 2018	1hr
P7	Director of an information management consultancy that uses Blockchain	Apr 2019	50m

**Participants 5 and 6 were interviewed together.*

3. Findings and discussion

A number of topics emerged from the interviews; while they are by no means exhaustive, they provide an interesting perspective on the potential applications of DLT for construction as identified by the participants along with some aspects for consideration in further research.

3.1 Challenges for construction

Any solution should first understand the challenges it is trying to solve. Many challenges to construction have been discussed in previous studies (Jennifer Li et al., 2019) and some are highlighted in the introduction of this paper. Initial discussions during the interviews involved clarifying some of the challenges in construction today that have the potential to be addressed in part by DLT. An overarching challenge offered is that, "*in the UK, the industry is very fragmented and is why the UK has one of the most expensive construction industries in Europe"* (P1). Both P1 and P2 highlight **adversarial pricing** where main contractors are "*undercapitalised and therefore using supply chain funds as cashflow to finance their businesses*" (P1), "*which means you are on a knife-edge all the time and it just requires a couple of things that tip you over the edge as Carillion showed*" (P2). *"Use of supply chain capital was a deliberate business policy used by Carillion. For clients to ensure against insolvency, they need to insist on different procurement procedures"* (P1). **Payments** *"is one of the most important things that really needs to be addressed"* (P6). P5 adds that, *"there are inefficiencies in the supply chain; arbitrary decisions, subjective decisions that delay payment, people who intervene, breakdowns in communication, a whole range of things that stop money passing down the supply chain. But also that interfere in the records of what have been provided".* And P7 explains that, "*construction contracts now are, literally, all stick and no carrot"* adding that, *"there's no incentive to over deliver, and all the risk is basically pushed down the supply chain".* Currently in construction supply chains, there is a reluctance to foster long-term relationships between main and sub-contractors due to the short durations of projects and physical distances between contractors. This results in poor information flows that provide little transparency and limited exchange of information and communication in general (Dallasega, Rauch, & Linder, 2018).

With regards **regulations**, P1 states another key challenge is "*lack of enforceability. People are not clear what it is they're enforcing and, therefore, can't hold people to account if they don't know who did what, when. There is lack of accountability".* This is mirrored by the key issues highlighted in the Hackitt Review (Hackitt, 2018).

These challenges are complex and overlap but are ultimately as a result of poor procurement practices that have been ingrained over many years and low profit margins that, before the global recession, encouraged main contractors to create business models around the use project funds to finance their business. These practices have continued into times of austerity resulting in clients requiring more for less and top tier contractors pushing the financial burden down through the supply chain putting quality and safety standards in jeopardy. DLT has the power to instil better behaviours in the way projects and assets are managed throughout an asset's lifecycle through providing visibility and traceability to clients and users (i.e. occupants) holding organisations and individuals to account. However, new practices require new legislation, new technology and new processes to be developed and deployed before better behaviours are likely to be seen in the construction industry.

3.2 Smart contracts and payments

A smart contract is an if/then, self-executing, computer-coded programme (Cohn, West, & Parker, 2017). When running on top of a distributed ledger, they offer the potential to automate many different types of activities within construction projects. They have been discussed as having the potential to replace traditional construction contracts where, in the context of the Accord Project (2019), P7 explains, *"It's producing that contract language programmatically using a data model so you can then produce your traditional contract but you can then have a data model that you can then hang things off and do all the things you can do with a programming language".* However, this is contrary to the view of the legal participants interviewed for this study. P4 states, *"one of the things it's not going to do is completely replace [traditional] contracts, purely because there are elements which require subjective viewpoints, for example, whether someone exercises reasonable skill and care".* P2 asks how far subjectivity can be removed from traditional contracts adding, *"You have to basically write a contract that doesn't contain the word "reasonable" in it. You need an "unreasonable contract" because there is your subjective element".* P5 says, *"it's so unlike a conventional contract that I don't want our discussions to suggest that there's anything in there that looks like a normal contract".*

P2 offers that a *"hybrid contract"*, a blend of a traditional and smart contract, will be used in the future *"giving flexibility to any judgement, which is necessary…in the context of a marriage with the subjective elements of the contract".* P4 adds that, in time, there will be off-the-shelf smart contracts, *"readymade sets so you shouldn't have to start from scratch every time you go to a project because it'll require a combination of lawyers and the coders and the commercial teams all coming together saying, well, this is how we want it to work".*

With regards the uses for smart contracts, they are proposed as a tool to measure contract performance, *"things like payments, ordering materials, anything that requires no level of judgement"* (P4). Smart contracts remove the flexibility that is seen in traditional contracts so P5 believes they *"only come into play after we've frozen our design development. There's no space, once you're into the world of smart contracts, there's no space for design development. You're going to get what you're going to get and you're going to pay for it so if you haven't crystallised that and made all the necessary decisions and being sure there's no more provisional items, there's no more change, no more refinement, you know, you're not ready for smart contract transactions".* In addition, P4 expresses the need to consider the Construction Act where "*you can issue Payless Notices, Payment Notices, you can report money in certain circumstances. So, whilst you can build that into the coding, there'll need to be a stepped process, it won't be, if you get to this milestone, you get paid".*

While payments are not the only and indeed main use case for smart contracts, they are perhaps the most commonly discussed use case as a result of DLT being initiated by Bitcoin. There are factors to overcome before payments and cryptocurrencies can be implemented in construction contracts such as enactment of new financial regulations but integration with current payment systems could be realised in the interim and result in elements of construction contracts being automated in the near future. Coding of every eventuality in a construction project is not practical but coding of activities that result in progressing some contract requirements, particularly those not requiring judgement (i.e. proof of delivery of goods to site), could be seen in the near future and can be integrated into existing systems such as automated data input into information models via IoT sensors.

3.3 BIM, collaboration and information sharing

It has been discussed that the limited success seen by adoption rates of BIM to date (NBS, 2019) is in part due to the industry's reluctance to collaborate and share information (Barima, 2017; Belle, 2017; Farmer, 2016). P1 states, *"The biggest problem with BIM Level 2 is that we are trying to apply a collaborative tool to a non-collaborative industry… People aren't sharing data which is what's causing the problems. It's trying to integrate processes using a digital mechanism on top of shaky foundations"*. P4 believes that DLT will *"help in terms of information sharing because there isn't any doubt as to who gave what, when and, technically, you can say, well, we can trust the information provided because no one would have tampered with it"*. However, P4 raises the issue of the General Data Protection Regulation (GDPR) where personally identifiable information is used as well as what happens when a contract is terminated and people have a 'right to be forgotten', their right to copyright and their right to the information contained within the distributed ledger. *"If they have a right to all the information being deleted, which is quite common, how does that impact your blockchain?"* (P4). While these issues must be considered before DLT can be successfully implemented and written into contracts for construction projects, P4 continues that "*it will certainly help exchange of information insofar as people have the technology to view it [and] the processes are put in place… Same as BIM when everyone was saying everyone's going to do BIM and everyone's going to work together in theory, but you have to actually implement it"*.

With regards the legal aspects of construction projects, when coupled with BIM, DLT has the potential to reduce *"things like onsite variations, which are very time consuming, requests for information, any disputes as to gaps in information or discrepancies in information. Hopefully that would all become a thing of the past if you're using blockchain and BIM and all the other tools. You have very clear information that everyone can rely on and is complete at the point you start construction. Because what really takes a lot of time in construction is the uncertainties and the onsite variations and the arguments later on"* (P4). *"Version control in BIM at the moment is not that good and I can see that an aspect of BIM going forward is going to know exactly who did what and when, when we have a dispute about it. If blockchain offers us that opportunity, then that's going to be helpful"* (P2). P1's view is that, *"Lack of clarity and phraseology is the biggest problem with disputes. Smart contracts could reduce the level of disputes due to the language used and promotion of standardisation of contracts. Smart contracts are more difficult to amend than traditional contracts and offer far greater transparency. People will be much more aware of what's in the contract"*.

In a previous paper, the authors proposed a conceptual approach to integration of DLT, BIM, IoT and smart contracts (J. Li et al., 2019); the interplay between each of these technologies is important in each of their abilities to effectively support construction projects. P4 sees them as "*tools to implement the contractual arrangement between the parties"*. Which tool is used at which time will depend on what the contract requires but as P6 indicates, "*there's a need to…realise that they have an element of dependency too"*. J. Li et al., (2019) provide a proof-of-concept for automating an installation task within a BIM-based project using IoT sensors and smart contracts that record transactions on a distributed ledger. Another example may not require the use of IoT where the trigger for a payment via a smart contract may come from human interaction rather than data sensors, particularly where judgement needs to be exercised.

3.4 Design development process

The design development process starts from concept of a construction project and tracks actual delivery through all of the changes and diversions from initial design to as-built state allowing visibility of the development and evolution of a project over the duration of the project. All participants raised a benefit of DLT as being the historical ledger that definitively says who did what, when and how. P1 believes that, if *"installed at the outset of the procurement process,"* it "*would give oversight of the delivery team and would give a massive boost to the regulatory system"*. P3 and P5 see value in pinpointing the problem to drive accountability backed up by data. P7 discusses the reduction in disputes between contractors and suppliers due to the "*publicly available ledger [where] you can see what happened and when"*. P6 adds that *"… the only way we get lessons learnt is by…knowing at what point we…diverted and whether that was a positive diversion or a negative one and maybe [DLT] is a way we can actually…do that and…learn better"* (P6).

This use case opens the door to driving other improvements in the design development process particularly around the drive for information *“that might be contracts, that might be other things that you can use to push for that information”* (P7) and may give *“rise to a much better record keeping system”* (P2). *“Smart contracts, hopefully, will create…a greater level of transparency that enables us very quickly to go back to source… We should look down the supply chain to origins and the integrity of what we’re getting…we never get interested in sub-contracts and supply contracts but blockchain enables us to do so”* (P5) and that provides a much more robust system of traceability. Traceability is at the centre of the Hackitt Review (Hackitt, 2018) and based on the findings from these interviews, it is something that can drive better practices and delivery throughout the asset lifecycle. In addition, P7 identifies new uses of information produced during a construction project or operation of a built asset such as performance data of components that manufacturers may be willing to pay for in the future allowing them to move toward a more servitised business model where equipment is leased rather than purchased.

3.5 Regulation and compliance

One of the failures of the construction industry is poor regulations and enforcement as stated by the Hackitt Review (Hackitt, 2018). Its response to this is a ‘golden thread’ of information or a digital record that performs the purpose of traceability as discussed in the design development process section above. P1 describes DLT as having the effect of *“someone looking over your shoulder”* and the importance of having oversight from the outset of a project. *“Use of technology to bolster regulation would ensure there were repercussions for having the blockchain as a regulatory tool that would reverberate throughout environmental standards, procurement, delivery etc.”* (P1). In addition, DLT can be used in identity management of building components or a “*passport*” that provides data upon request such as ratings against which to prove compliance with building regulations. P1 believes that DLT *“will lend integrity to building safety and accountability”*, that it can make it easier to *“enforce the delivery processes to quality and safety standards”*, that it will force *“people to account in quality factors [and] will change how people operate”.*

Although the Blockchain is 10 years old, being released alongside Bitcoin in 2009 (Nakamoto, 2008), academic research on DLT for use in construction only began in 2017 (Jennifer Li et al., 2019). Given its nascence for construction, P4 believes that regulations for DLT in construction will be driven from outside the industry (i.e. in Europe or by other industries such as fintech) but *“how applicable those regulations will be to [construction] and how they will interact with say, the Construction Act, and such will get complicated. I think there will probably be case law first, before regulation just by the nature of things”* (P4).

4. Areas for further consideration

To demonstrate clear outcomes of this study and to inform future research in the field of DLT in construction, a number of areas requiring further consideration that arose during the interviews have been tabulated in Table 2. Each area has been described briefly and suggested activities to support further investigations given. While this table provides clear areas for consideration based on the interviews conducted for this study, an extensive list of challenges and opportunities related to DLT in construction based on a thorough systematic literature review is given in (Jennifer Li et al., 2019).

Table 2: Areas for further consideration

Area for consideration	**Description**	**Implications for DLT in construction**	**Suggested activities**
Procurement processes	Appointment practices based on a lowest tender wins ethos put in jeopardy safety and quality standards of built assets; procurement is not digitised and therefore does not support technological advancement of the industry in its current state.	DLT (and other digital systems such as BIM) require digital input to function optimally. A move toward electronic, digitised procurement processes would give a boost to digital transformation that the construction industry requires.	Industry should take steps to digitise current procurement processes to result in computable documentation (i.e. exchange information requirements) that can be transferred directly into smart contracts and information models to speed up activities and support automation.
Poor payment practices	Payments can take up to 120 days to be processed from the main contactor to subcontractors which negatively affects the supply chain. Disputes around quality and scope often arise delaying payments.	Undisputable, validated and verified proof that work has been completed to specified requirements will force main contractors to pay sub-contractors quicker, especially if written into the contract by the appointing party.	Demonstrate proofs-of-concept through simulations and pilot studies to show how proof is recorded on a distributed ledger.
Lack of collaboration and information sharing	Poor trust relationships between contracting parties, issues around intellectual property rights (IPR) and current payment practices discourage parties to collaborate and share information throughout project delivery.	Proof-of-ownership and timestamping on a distributed ledger can alleviate many of the issues around IPR resulting in a change in trust and therefore generate more willingness to share information and collaborate.	Demonstrate proofs-of-concept to show parties how their IPR can be protected using DLT. Increased collaboration and information sharing will support better delivery of projects with fewer disputes between the parties.
Lack of enforceability of regulations	Current policies and processes are not sufficiently robust to check and ensure regulations are complied with.	Immutable recording of certifications and compliance with regulations will provide proof that projects and assets are compliant. The new system will encourage contractors to work to better safety and quality standards if their work is to be recorded forever.	Review current regulations and compliance guidance. Develop new policies and processes to create a more compliant and transparent environment surrounding built assets. Consider DLT as a platform for recording regulations and compliance.
Complexity of construction contracts and the extent to which they can be automated	Subjectivity based on human experience and judgement is required in the delivery of construction contracts. These elements are not yet automatable as artificial intelligence is not sufficiently advanced to replace human judgement.	Some aspects of construction contracts can be automated while others require a human to interject. While technology develops to the extent that these aspects can be replaced by AI, smart contracts can be used for those activities not requiring judgement.	Investigate how far traditional contracts can be automated using smart contracts accounting for the level of subjectivity required in the delivery of construction contracts. Develop standardised off-the-shelf smart contracts to speed up processes and be more accessible.
General Data Protection Regulation (GDPR)	GDPR gives individuals more control over personally identifiable data.	An immutable ledger is in direct contrast to GDPR's 'right to be forgotten" where individuals have the right to demand their personally identifiable data be permanently deleted.	Consider GDPR in any DLT-based solution that records personally identifiable data ensuring that the solution is compliant with the regulation.

The areas highlighted in Table 2 consider aspects of the construction industry that are much boarder than the context in which they are described in this paper. Each requires consideration regardless of whether DLT is considered as part of a solution to improve current practices or comply with certain regulations. DLT is not offered as a standalone solution to solve the construction industry's many challenges, however, it is offered as an option for consideration alongside alternative options to support digital transformation and reform of the construction industry.

5. Conclusions

The aim of this study was to engage with senior industry practitioners and academics from across the UK construction industry to identify potential drivers for implementing distributed ledger technology (DLT) in this complex industry. Seven semi-structured interviews took place over a one-year period and discussed the sector challenges that can potentially be supported by DLT. While it is not a standalone solution to these challenges, DLT can be part of the solution due to its unique characteristics of decentralisation and immutability holding people to account through traceability and visibility. Four topics were discussed with interview participants alongside the industry's challenges: smart contracts and payments; BIM, collaboration and information sharing; the design development process; and regulations and compliance. This is by no means an exhaustive list of DLT use cases and there are many overlaps within these topics but each has different requirements for a DLT-based system whether that be integration with other technologies (i.e. BIM, IoT and smart contracts), enactment of new legislation or new business processes, among others. Participants identified future use cases that could be realised as a result of the initial purpose of DLT, for example, more advanced uses of information beyond that of a digital record such as performance analysis of building components that a manufacturer might be willing to pay for and better record keeping.

Some aspects to be considered arose from the interviews including: how GDPR will affect information held in a distributed ledger; coding of smart contracts to account for The Construction Act with regards payments; and implementation of smart contracts where reasonable skill and care or judgement of a human are required.

The limitations of this research include: the limited number of interviews that took place providing a limited perspective of DLT in the construction industry; and four of the seven participants had a legal background which is likely to have skewed the findings toward their collective perspective.

The interviews presented in this paper were conducted alongside a study to develop a framework for the implementation of DLT in the construction industry (Jennifer Li et al., 2019), the findings of which informed the framework's development. Further research will involve additional interviews with industry practitioners and academics and the addition of public and private sector clients and asset users (i.e. building occupants) to ensure that the framework is applicable to all DLT use cases and for different types of projects; and to further extend the framework to include a roadmap to implementation of DLT for specific use cases at an industry scale.

Acknowledgements

The authors would like to thank each of the participants for their time and enthusiasm given during the interview process and the valuable contributions they made to this study and others that have been informed by the findings along the same lines of enquiry.

References

Accord Project. (2019). Accord Project. Retrieved 20 May 2019, from https://www.accordproject.org/

Barima, O. (2017). Leveraging the blockchain technology to improve construction value delivery: the opportunities, benefits and challenges. In K. Hall (Ed.), *Construction Projects* (pp. 93–112). New York, NY, USA: Nova Science Publishers, Inc.

Belle, I. (2017). The architecture, engineering and construction industry and blockchain technology. (G. Ji & Z. Tong, Eds.), *Digital Culture 数码文化 Proceedings of 2017 National Conference on Digital Technologies in Architectural Education and DADA 2017 International Conference on Digital Architecture*. Nanjing: China: China Architecture Industry Publishers.

Booth, R., & Davies, C. (2018). Expert lists litany of serious safety breaches at Grenfell Tower. Retrieved 4 June 2018, from https://amp.theguardian.com/uk-news/2018/jun/04/expert-lists-litany-of-serious-safety-breaches-at-grenfell-tower

Braun, V., & Clarke, V. (2012). Thematic Analysis. In H. Cooper (Ed.), *APA handbook of research methods in psychology, Vol 2: Research designs: Quantitative, qualitative, neuropsychological, and biological.* (Vol. 2, pp. 57–71). Washington: American Psychological Association. https://doi.org/10.1037/13620-004

Cohn, A., West, T., & Parker, C. (2017). Smart After All: Blockchain, Smart Contracts, Parametric Insurance, and Smart Energy Grids. *Georgetown Law Technology Review*, *1*, 273–304. Retrieved from https://www.georgetownlawtechreview.org/wp-content/uploads/2017/04/Cohn-West-Parker-1-GEO.-L.-TECH.-REV.-273.pdf

Dallasega, P., Rauch, E., & Linder, C. (2018). Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Computers in Industry*, *99*(April), 205–225. https://doi.org/10.1016/j.compind.2018.03.039

Dorri, A., Kanhere, S. S., Jurdak, R., & Gauravaram, P. (2017). Blockchain for IoT security and privacy: The case study of a smart home. In *2017 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)* (pp. 618–623). Kona, HI, USA: IEEE. https://doi.org/10.1109/PERCOMW.2017.7917634

Egan, J. (1998). *Rethinking Construction*. *HMSO*. Retrieved from http://constructingexcellence.org.uk/wp-content/uploads/2014/10/rethinking_construction_report.pdf

Farmer, M. (2016). The Farmer Review of the UK Construction Labour Model: Modernise or Die. *Construction Leadership Council*. Retrieved from http://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2016/10/Farmer-Review.pdf

Hackitt, J. (2018). *Building a safer future - Independent Review of Building Regulations and Fire Safety: Interim Report*. *HM Government*. https://doi.org/ID CCS1117446840

Latham, M. (1994). *Constructing the Team*. *HMSO*. Retrieved from http://constructingexcellence.org.uk/wp-content/uploads/2014/10/Constructing-the-team-The-Latham-Report.pdf

Li, J., Greenwood, D., & Kassem, M. (2019). Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in Construction*, *102*, 288–307. https://doi.org/10.1016/j.autcon.2019.02.005

Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M. (2019). A proposed approach integrating DLT, BIM, IOT and smart contracts: Demonstration using a simulated installation task. In *International Conference on Smart Infrastructure and Construction*. Cambridge.

Nakamoto, S. (2008). *Bitcoin: A Peer-to-Peer Electronic Cash System*. *Www.Bitcoin.Org*. Retrieved from https://bitcoin.org/bitcoin.pdf

NBS. (2019). *National BIM Report 2019*.

Popov, S. (2018). *The Tangle*. Retrieved from https://assets.ctfassets.net/r1dr6vzfxhev/2t4uxvsIqk0EUau6g2sw0g/45eae33637ca92f85dd9f4a3 a218e1ec/iota1_4_3.pdf

Risius, M., & Spohrer, K. (2017). A Blockchain Research Framework: What We (don't) Know, Where We Go from Here, and How We Will Get There. *Business and Information Systems Engineering*, *59*(6), 385–409. https://doi.org/10.1007/s12599-017-0506-0

Symonds, T., & Ellison, C. (2018). Grenfell Tower cladding failed to meet standard. Retrieved 14 February 2019, from https://www.bbc.co.uk/news/uk-43558186

The Influence of the Blockchain Technology on Trust in construction Supply Chain Management

Xiaoning Qian[1,*], Eleni Papadonikolaki[1]
[1]The Bartlett School of Construction and Project Management, UCL
[*]email: e.papadonikolaki@ucl.ac.uk

Abstract

Blockchain technology is booming in many industries. Its application in supply chain management is also gradually increasing. Supply chain management has long been committed to reducing costs and increasing efficiency and is trying to optimise resources and reduce the sector's fragmentation. Trust has always been an important factor in managing supply chain relationships, and it also affects the efficiency of supply chain operations. Blockchain technology provides solutions for data tracking, data sharing, and smart contracts for supply chain management. These applications help to enhance the sources of trust in supply chain management and provide contractors with protection mechanisms to avoid the risks and costs of opportunistic behaviour in collaboration. This study is based on semi-structured interviews and publicly-available information from experts in blockchain and construction supply chain management. By content analysis, this paper discovers features and applications of the blockchain technology, explores sources of trust in supply chain management and explains and demonstrates the impact of blockchain technology on trust in construction supply chain management.

Keywords: blockchain technology, supply chain management, application, trust, experience

1. Introduction

A supply chain (SC) is defined as a network of suppliers, factories, warehouses, distribution centres, and retailers. Supply chain management (SCM) is committed to improving the performance of individuals across the entire supply chain (Hofmann, 2016). According to Pryke (2009), supply chain tendencies in the construction industry become loose and lead to an increase in transactions and a decrease in the average value. For a long time, the problem of poor trust in supply chain management in the construction industry has been magnified because of fragmented cooperation (Pryke, 2009). The key to excessive waste and looseness is trust among parties (Sterman, 2000). Blockchain technology is a possible way to provide a smoother information sharing mechanism and preserve security or transactions (Nakamoto, 2008). Blockchain technology works as a distributed database that maintains a continually growing list of data records to prevent tampering and modification (Morris, 2016; Nakamoto, 2008; Popper, 2016).

The research aim is to find out what blockchain technology can bring to trust in construction SCM. The research question is: *how does the blockchain technology change trust in SCM in construction industry and in which dimension or aspect*? This research will start with a literature review, looking for the characteristics of blockchain technology and existing applications, and analyse the trust of SCM and the construction industry. Then the methodology will be elaborated, with specific methods and implementation content. Next, the study will present and analyse the collected data, try to establish the mechanism and relationship, and compare the analysis concludes with the existing theories. The limitation will also be reflected. Finally, the study will conclude the thesis and give recommendations to participants and further research.

2. Sources of Trust in SCM

Studies have shown that corporate activity and interaction are influenced by previous levels of trust (Gulati & Nickerson, 2008). A better level of trust will increase the efficiency of the later cooperation. Good interaction and joint work in SCM always require trust (Morgan & Hunt, 1994). In supply chain management, trust is also considered to be a willingness to agree with partners and confidence in them (Moorman et al., 1992). There are two traditional theories of trust establishment. One is based on economics. Scholars in transaction cost economics see trust as a substitute tool for cost-effective coordination and risk management (Bromiley & Cummings, 1995). The second theory reflects the views of psychology and sociology, which is the view that this study adopts.

Psychologists divide the impact of trust into micro-level and macro-organisational aspects. Manu (2014) summarises trust in supply chain management as inter-organisational trust, agency trust and inter-entity trust. The more micro-trusted the subject, the higher the influence of the individual's psychological factors. In a macro and more rational perspective, trust can be built on potential benefits or losses. Wong and his colleagues (2008) describe the sources of trust in the following dimensions.

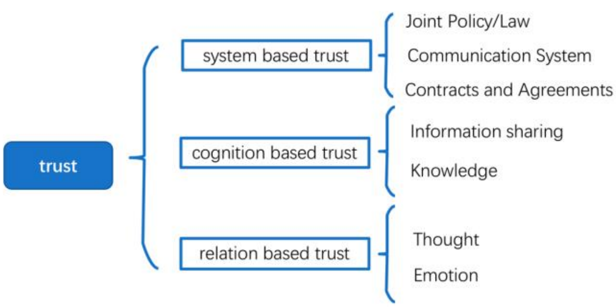


Figure 2.1: Sources of trust (Wong et al, 2008)

Rational trust is seen as believing that the other party will take opportunistic actions to ensure the company's interests (Tejpal et al 2013). Manu (2014) divides the foundation of trust in supply chain management in the construction industry into three categories below.

Relationship

Relationship-based trust comes from resource swaps and opportunity sharing in past collaborations. This kind of trust exists before the establishment of the project cooperation relationship, free from the limitations of personal experience, and is a more objective relationship at the organisational level. Akkermans et al. (1999) confirmed that the closer the cooperation among supply chain partners, the more data they share. This will increase the profitability and performance of all parties.

Competence

In construction projects, trust also comes from the company's reputation and resources, such as technological advantages, capital or market share (Das & Teng, 2001). At the same time, corporate performance and corporate risk also affect the company's capabilities, because it affects the difficulty of successful completion of the project.

System

At the rational and inter-organisational or macro level, trust can come from human and non-humans, such as computers and automated systems. Contract execution environments and sociocultural identity can form system-based trust. Such mechanisms provide an objective communication and monitoring channel to promote the development of trust in Parties.

Latham's (1994) construction industry report pointed out that construction is heavily dependent on competitive bidding and confrontation, which reduces the quality of trust and increase costs. The fragmentation of construction projects challenges the adjustment of risk management, integration of resources and management of performance in supply chains. Long-term supply chain relationships are compromised when short-term returns are treated as a top priority (Smyth, 2010, 2011). Specific issues include, for example, arrears, credit difficulties, bidding/contract drafting fees, and information asymmetry (Paunov, 2011; Manu, 2014).

3. Applications of the Blockchain Technology in SCM

Scholars state that blockchain technology offers solutions and may disrupt many industries (Kshetri, 2017). In the construction supply chain, some primary solutions of blockchain technology have been applied. Till now, blockchain technology has been applied to smart contracts, banks, and supply chains (Gatteschi et al., 2018). Each block in the network contains data and timestamp of the previous block of transaction creating thus a distributed ledger of information in the network (Nakamoto, 2008). Recognised blockchain networks can be divided into three categories: public blockchains without any access properties; semi-distributed consortium blockchains authorised by federation administrators (Zhu et al., 2018).

The main characteristics of blockchain are described as decentralization and transparency (Raval, 2016). Transparency is defined as the level of how outsiders can detect into the working system (Awaysheh & Klassen,2010). Blockchain technology is suitable for transparency improvement due to its unchangeable ledgers and distributed natures. With real-time data sharing distributedly, stakeholders can identify whether the quality, location, treatment, or any other details and procedures are qualified. Digital ledgers provide a proven, reliable solution with distributed data, which establishes a trusted relationship network within blockchain technology (Gartner, 2016). The main features of blockchain technology are tracking, recording and provenance and can be illustrated through the following examples

Maersk, the world's largest container carrier company, used the blockchain technology into the logistics in cooperation with IBM (Popper & Lohr, 2017). It tracks the shipping containers with the location, time, temperature or other condition information by GPS or sensors. The tracking function brings another function: recording. The cross-border shipment used to take several days before the application in the case. With blockchain technology, it takes minutes to be accomplished. With the implementation of blockchain technology, it can cut the enormous cost on record work and labour source.

Blockchain technology also provides provenance. A smart contract is a unique feature that runs in a digital environment is the ability to create algorithms and programs that can be partially or wholly executed or executed when certain conditions occur. It is a kind of technology to replace the complicated and troublesome interpersonal interaction (Crosby et al, 2016). The stakeholders in different levels would have more flexibility to act their best and create more value for the whole ecosystem (Koetsier, 2017).

The fragmentation of construction requires higher integration in supply chains (Smyth, 2010). Trust is an important factor in improving the efficiency of supply chain management (Morgan & Hunt, 1994). Manu (2014) divides the foundations of trust relationships among supply chain organisations in the construction industry into systems, relationships, and competence. However, it does not explain the specific relationship between the partners to promote trust. This study provides a lens for how blockchain technology affects supply chain management, especially in the construction industry. It can bring inspiration to future business development ideas which supply chain companies in construction can use to provide solutions for inter-firm trust relationships. Blockchain technology initiatives will also gain a better understanding of the needs of SCM in construction industry.

4. Methodology and Methods

This research used semi-structured interviews and an interpretivist lens to collect data and use thematic analysis to analyse and reach a qualitative conclusion (Bryman, 2012). This study is based on a mixture of narrative research and grounded theory research and a mixed data collection strategy. The data from this study was derived from 10 interviews and two public lectures from experts on blockchain applications.

The interviewees are mainly selected from industries of blockchain technology, supply chain management, and construction project. Their selection was crucial for research validity and relevance. The three themes and interviewees profiles are listed in Table 4.1The semi-structured interviews lasted around half an hour per interview. The first two introductory questions are used to provide an industry orientation for the interviewee and provide a basic understanding of the blockchain or supply chain concepts. Then the following three questions were about each topic they belong to. Finally, one or two discussion items were asked based on the previous problems discussed before, or to determine the individual subjective tendency of the interviewee about the application of the blockchain technology in SCM.

Table 4.1: Profiles of interviewees and data sources

Theme		Sources of data (interview or public lecture)
Blockchain	Interviewee 1A	Research fellow in blockchain solutions
	Interviewee 1B	Professor on computer security
	Public lecture 1C	6 Blockchain experts in technology
	Public lecture 1D	8 Blockchain experts in applications
Applications of Blockchain in SC	Interviewee 2A	Professional in operating electronic payment
	Interviewee 2B	Business developer of Internet of Things (IoT)
	Interviewee 2C	Economics expert researching smart contracts
Construction SCM	Interviewee 3A	Construction procurement manager
	Interviewee 3B	Director of a logistics firm on construction materials
	Interviewee 3C	Operation officer of logistics firm for construction materials
	Interviewee 3D	Professional in port warehouse (logistics recorder)
	Interviewee 3E	Project manager of a construction firm

Some research limitations of the research design are as follows. As the interviewees' responses do not guarantee research validity, the interview time was adjusted to positively and succinctly answer research questions without reduction in data quality. Trust is divided into interpersonal and inter-organisational levels and this study only focused on relational instead of micro or interpersonal factors of the trust developed, so as to be consistent to the main research question about SCM. Also, the interviewees' knowledge and cognition are subjective, so this study cannot promise an entirely objective conclusion but instead the interpretation and construction of a reality drawn upon their data. Through interviews and data analysis, this study can only qualitatively give specific explanations of the problem, but it cannot provide more precise quantitative judgments.

5. Applications of Blockchain Technology in Construction

The interviews with practitioners considered the two characteristics of the blockchain, decentralisation and transparency, have their unique applications, advantages and disadvantages. By interviewing people in the e-tracking, Smart Contract, and Finance industries who are doing blockchain-related research, it was extracted that blockchain has the following applications in the supply chain.

1) Tracking

The function of tracking was initially derived from the Internet of Things (IoT). Long before the blockchain technology emerged, the IoT has begun to focus on instant peer-to-peer dissemination of information. Interviewee 2B tells us: *"The most significant advantage is the increased efficiency of the distribution of information and knowledge. The information dissemination mechanism provided by the blockchain will significantly enhance the maintenance and after-sales." "The instant tracking method can save 70% of the after-sales cost.",* according to interviewee 1A.

At the same time, the labour costs required to record progress will be significantly reduced. Interviewee 3D stated: "*Once information is passed to the next level of contractors faster than ever before, we can reduce the dates of inventory turnover and improve other indexes related to the efficiency of supply chain management."*

2) Contracting

Interviewee 2C, who has done research on smart contract states that individual industry contracts given through electronic technology can help people avoid trivial contract drafting and inspections. Interviewee 2C stated: "*Once a party has more critical information that is not publicly available, it is very likely that it will avoid the contractual restrictions and draw benefits that are not beneficial to the other party. Smart contracts are committed to providing the most detailed and dependable terms of the agreement within the legal scope of the most regulated and widely used."*. The goal of blockchain technology is to automate the contract, making it infinitely perfect, and making people's distrust of the other party signing the agreement to a minimum, thereby improving the efficiency and legal protection of the participants in signing the contract.

3) Money transfer/Payment

Many banks have applied blockchain technology to their financial systems. The main reason is that its peer-to-peer transaction recording method can save workload for centralised processing in traditional banking systems. According to interviewee 3E, the project manager, and interviewee 3B, the director, one of the significant problems in supply chain management is the management of money flow. In interviewee 3B's words: *"The biggest problem is the payment problem. Few people will complete the transfer on the date of payment."*. Interviewee 3E explains: *"Arrears are not the deliberate act of most people. Their capital chains are also affected by other arrears, especially small companies. This is an industry-wide problem, and it will only be better if everyone improves."*

In larger projects, many small and medium-sized enterprises will face the threat of direct bankruptcy once the upstream or downstream contractors' default. On the one hand, the financial transfer system of the blockchain plus the detailed design of the smart contract can guarantee the proper execution of the transfer. They can significantly reduce the ambiguity of the contractual transaction date and other default issues faced by the companies.

6. Changes of Trust Mechanisms in Supply Chain Management

As mentioned in the literature review above, the experience of collaboration or the reputation that companies have built on cost is a source of confidence across the supply chain industry. From the interviews, interviewees 3B, 3C, and 3E concurred that trust came from three aspects. The relationship is illustrated in Figure 4.1. As is shown in the figure, the trust between suppliers comes from the cost reduction, which depends mainly on the level of the risk. They believe that a company's existing reputation, cooperation history and industry norms can help reduce the risk of cooperation, thereby enhancing trust.

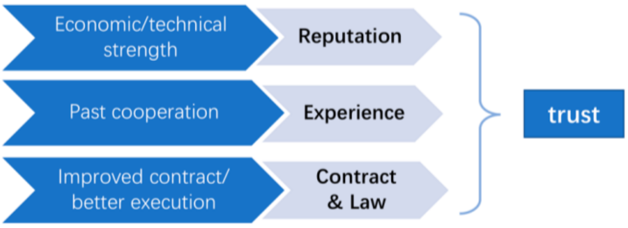


Figure 6.1: Sources of trust in construction SCM

1) Reputation

Interviewee 3B stated: *"Reputation is usually recognised in the industry, for example, a list of companies that are identified by an official or authority is considered to be more trustworthy."* In the interview, interviewee 3B clarified by saying: *"When working with state-owned or partially state-owned enterprises, we would simplify the review or inspection process to reduce pre-contact costs. Because state-owned companies have national credibility support, we will trust such companies more."* Interviewee 3B mentioned that this is also because state-owned enterprises are often able to obtain bank loans and trust in all aspects in the first place, making them less prone to economic crises. *"There is less condition of default.",* interviewee 3A explains the reason why reputation is a source of trust. At the same time, interviewee 3C emphasizes: *"In the supply chain of the industry, technical or management advantages are also considered part of the reputation. These advantages mean that companies with advantages have scarce resources in the industry."* Although there may be cases where the bid price is too high, people usually choose to be willing to work with them and trust them.

2) Experience

According to interviewee 3B, past cooperation experience is considered to be the most common source of trust in supply chain cooperation: "*During the first cooperation between contractors, both parties spend a lot of time and energy to test each other. So, we would spend more time on information transfer and coordination. Once the results of initial cooperation or multiple cooperation are satisfactory to both parties, and there are no other conflicts of interest, we will choose to continue to cooperate and strengthen trust, reducing efforts to guard against and suspect*." For interviewee 3E, although this is a source of trust for most vendors in the industry, *"it takes much energy from the first collaboration to the next mutual trust. Not all partners can turn out to be long-term partners. This conversion rate from 'strangers' to 'trusted partners' is not very high."*

3) Contracts and laws

Another primary source of trust is contracts and legal norms. In the absence of cooperation experience or a massive corporate aura, the agreement is considered to be a kind of enforcement guarantee. The more detailed the contract, the stronger the security that the signing party brings. Also, the degree of perfection of contracts and laws and their enforcement are the most fundamental guarantees for corporate cooperation. Interviewee 3B stated: *"As this safeguard mechanism is strengthened, the difficulty of cooperation between enterprises will be reduced because they can build enough trust. This kind of trust does not require past cognitive help, because the law and the contract can guarantee that the losses and costs brought by the other party's uncertain behaviour in the cooperation are adequately compensated".*

The interview data shows that trust comes from reputation, past cooperation experience and mandatory execution such as contracts, laws and regulations. Based on the data above, the functions of trust of blockchain applications could be illustrated as shown in Figure 4.2.

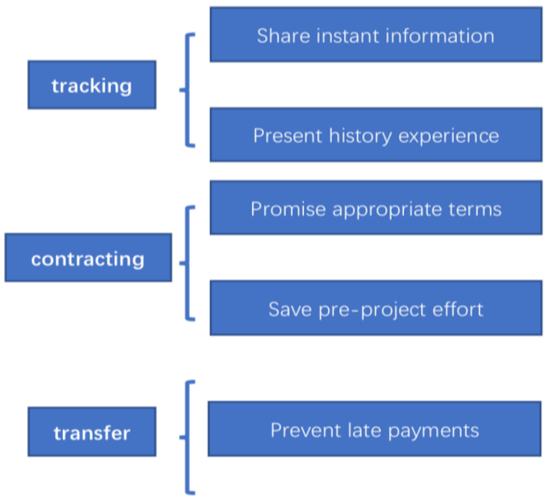


Figure 6.2: Functions of trust of blockchain applications

In this way, the source of information, the way it flows, and the enforcement of specifications will affect trust and ultimately affect the effectiveness of supply chain management. The blockchain technology can be seen as a third party that provides transparency and reliability. *"Once certified by an authority or industry, it will have the ability to bring credibility proofs that increase trust between companies.",* indicates the expert in the public lecture 1C. When applied, this technology will improve the flow of information and knowledge, helping members of the network optimise resource allocation and reduce costs. So, the technology can increase trust while reducing the need for trust in collaboration. Better contract integration and transfer methods enhance the supervision and execution of external management (legal and financial); transparent real-time tracking and decentralised data sharing bring more reasonable rights and openness to all parties.

From the interview data, three applications of blockchain: tracking, contracting, and transfer have the functions of sharing instant information, presenting history data, promising terms, saving pre-project effort, and preventing deferred payments. The direct sources of trust in supply chain management in the construction project industry are reputation, experience and contacts. Data tracking can display historical data, which can replace the actual past cooperation to some extent. Contracting can provide detailed terms and enhance the contract and execution together with the prevention of deferred payments. In this way, blockchain applications enhance trust in SCM. The relationships among these concepts are illustrated below in Figure 6.3. Through the analysis, the process of how blockchain technology affects supply chain management parameters by influencing and altering the trust dimension is explained in Figure 6.4.

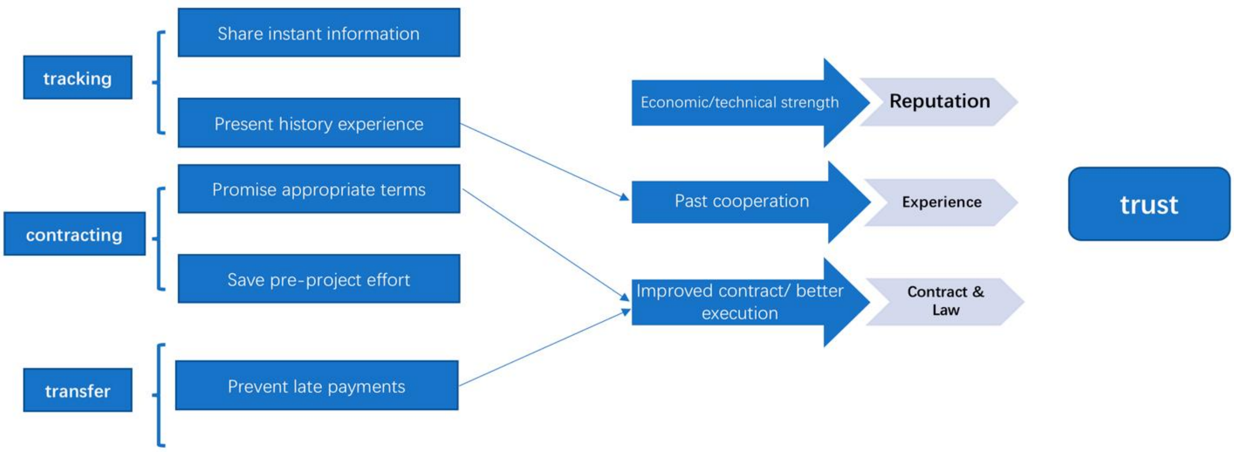


Figure 6.3: Influence of blockchain applications on sources of construction SCM trust

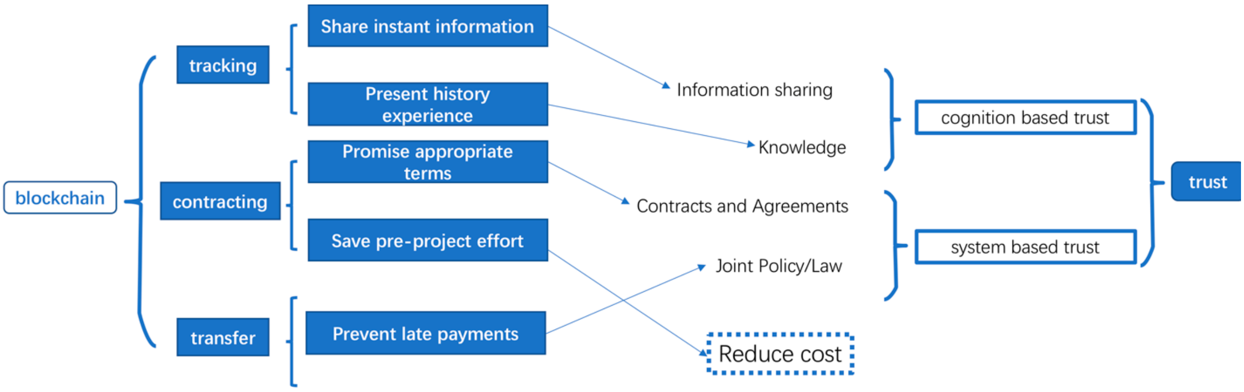


Figure 6.4: Influence of Blockchain Applications on SCM Trust Dimensions

Information sharing and historical display are ways to enhance cognition-based trust. Optimized contractual treaties and effective payment mechanisms increase the credibility and feasibility of the system. Besides, quality smart contracts reduce many of the upfront efforts for the project, which directly reduces costs. With the application of blockchain technology, members of the supply chain industry do not need to spend a lot of money and efforts to establish peer-to-peer repeated cooperation to gain trust. They only need to trust a blockchain trading system that has been designed well. This kind of management tool is somewhat similar to the alliance, but it has a more transparent sharing mechanism, less centralised tendency and more comprehensive and reasonable institutional treaty than the ordinary business alliance. Information sharing, knowledge, contracts and agreements and policy contribute to the cognition based and system-based trust according the classification of Wong et al. (2008), as shown previously in Figure 2.1.

7. Discussion and Conclusion

From the empirical fieldwork, this study identified and analysed how the characteristics of the blockchain, transparency and decentralisation, and its applications influence the way people trust among partners in supply chains. With the three existing applications of blockchain technology in the supply chain, the blockchain technology can increase the source of trust among contractors. Answering the main research question, it can be said that regarding the dimension of the trust sources, the blockchain applications mainly enhance trust by affecting the cognition-based trust and the system-based trust. At the same time, for construction supply chain management, the function of contracting is expected to reduce the cost of contract signing or bidding and solve the capital flow issues in projects.

Through semi-structured interviews, this paper identifies the characteristics of the blockchain technology, discusses the applications of blockchain in SCM, and points out how they affect trust in construction SCM. This study goes a step further by explaining the reason that clear rules or sufficient tracking information brought by the blockchain technology can improve the "trust relationship" through the system-based and cognition-based trust. It can directly reduce the cost and need of building trust in the early stages of cooperation.

This conclusion is in part in line with the idea that more historical data and collaborative experience will reduce opportunistic behaviour and increase trust. The improvement of smart contracts and the strengthening of enforcement will help reduce the need for trust. The improvement of the mandatory external mechanism will reduce the uncertainty in the cooperation process. Also, the conclusion resonates with the classification of sources of trust: relationship, competence and system. Interview data extends this view, further explaining that technical strength or reputation can lead to trust because companies with good representations can have more credit lines, thereby reducing risk in cooperation. Interview data indicates that construction industry practitioners have shown proper expectations for blockchain technology to solve trust problems, especially concerning delayed project payments and credit issues (Paunov, 2011).

When selecting the type of the blockchain network, this paper mainly focused on the open blockchain network, ignoring the private blockchain network. In private or semi-federal blockchain networks, the degree of transparency and decentralisation will diminish as licenses are not fully issued. The analysis also did not consider the cost of developing blockchain technology solutions.

For supply chain managers, increasing efficiency and reducing total cost has always been an important goal. Based on the findings above, the practical implications of this study and recommendations for leveraging the potential of digitalisation to manage trust are: 1) improving the contract details, 2) improving the level of information sharing and 3) being sensible to new technologies like the blockchain. Improving the blockchain technology itself is very important. Whether the current market and social development conditions allow decentralised business models remains to be studied. Among the publicly decentralised information, some are not wholly decentralised in the current application scenario. For example, registration of private information. The extent to which blockchain technology can develop depends on the degree of social acceptance of decentralisation, which requires more research on social ethics. There are other parts of trust in supply chain management, such as object trust and mechanism trust (Tejpal et al, 2013). More research can be done on different types of trust in construction supply chain management. With the wave of the powerful blockchain technology, the way of how different types of enterprises could rely on blockchain technology to obtain tangible benefits will be the focus of future research.

References

Akkermans, H., Bogerd, P., & Vos, B. (1999). International Journal of Operations & Production Management, 19(5/6), 565-582.

Awaysheh, A., & Klassen, R. (2010). International Journal of Operations & Production Management, 30(12), 1246-1268.

Bromiley, P., & Cummings, L.L. (1995). Transaction costs in organizations with trust. In: Bies, R., Sheppard, B., Lewicki, R. (Eds.), Research on Negotiation in Organizations (pp. 219–247). Greenwich: JAI Press.

Hofmann, E. (2013). Supply Chain Management: Strategy, Planning and Operation, S. Chopra, P. Meindl, 5th ed, ISBN:978-0273765226. Journal of Purchasing and Supply Management, 19(3), 212-213.

Crosby, M.; Pattanayak, P.; Verma, S., & Kalyanaraman, V. (2016). Blockchain technology: Beyond bitcoin. Appl. Innov. 2, 6–10.

Das, T., & Teng, B. (2001). Trust, Control, and Risk in Strategic Alliances: An Integrated Framework. Organization Studies, 22(2), 251-283.

Gartner. (2016). The Bitcoin Blockchain: The Magic and the Myths.

Gulati, R. & J. A. Nickerson. (2008). Interorganizational trust, governance choice, and exchange performance. Organization Science, 19(5), 688-708.

Koetsier, J. (2017). Blockchain Beyond Bitcoin: How Blockchain Will Transform Business in 3–5 Years.

Manu, E. (2014). Supply Chain Management Practices in Construction and Inter-organisational Trust Dynamics, PQDT - UK & Ireland.

Morgan, R., & Hunt, S. (1994). The commitment-trust theory of relationship marketing. Journal of Marketing, 58(3), 20.

Morris, D.Z. (2016). “Leaderless, Blockchain-Based Venture Capital Fund Raises $100 Million, And Counting,” Fortune.

Nakamoto, S. (2008). "Bitcoin: A Peer-to-Peer Electronic Cash System," Bitcoin.org.

Paunov, C. (2011). The global crisis and firms' investments in innovation. Research Policy, 41(1), 24-35.

Popper, N. (2016). "A Venture Fund with Plenty of Virtual Capital, but No Capitalist," New York Times

Popper, N., & Lohr, S. (2017). Blockchain: A better way to track pork chops, bonds, bad peanut butter? https://www.nytimes.com/2017/03/04/business/dealbook/ blockchain-ibm-bitcoin.html.

Pryke, S. (2009). Innovation in the Built Environment. Oxford, UK: Wiley-Blackwell.

Raval, S. (2016). Decentralised applications: harnessing Bitcoin's Blockchain technology First

Sterman, J. (2000). Business dynamics: Systems thinking and modeling for a complex world / John D. Sterman. Boston: Irwin/McGraw-Hill.

Tejpal, G., Garg, R., & Sachdeva, A. (2013). Measuring Business Excellence, 17(1), 51-71.

Gatteschi, V., Lamberti, F., Demartini, C., Pranteda, C., & Santamaría, V. (2018). Blockchain and Smart Contracts for Insurance: Is the Technology Mature Enough? Future Internet, 10(2), .

Wong, Cheung, Yiu, & Pang. (2008). A framework for trust in construction contracting. International Journal of Project Management, 26(8), 821-829.

Zhu, Y., Riad, K., & Guo, R. (2018). New instant confirmation mechanism based on interactive incontestable signature in consortium blockchain. Frontiers of Computer Science, pp.1–16.

Blockchain in construction – hype, hope, or harm?

Dimosthenis Kifokeris[1, *] and Christian Koch[1]
[1]Chalmers University of Technology
[*]email: dimkif@chalmers.se

Abstract

Business and public interest and investments in digital ledgers, smart contracts and virtual currencies such as bitcoin, has skyrocketed. Blockchain is indeed a hyped technology – and should therefore raise healthy skepticism. During construction production, projects and the involved companies take on a disintegrated economic flow and allocation of economic resources; these include supplies of materials and services, payments, accounting tasks, and other economic decisions, that are often treated second-hand by site management, subcontractors, transport companies, retailers and material suppliers. Within such a situation, blockchain technologies can maybe create value for stakeholders in handling this economic flow and integrating it with other information and material flows. So, in this sense, blockchain represents a hope for construction; however, this paper critically scrutinizes blockchain for construction, in trying to answer the question whether it indeed constitutes hope, or it is harmful. The paper will report from an ongoing study and development project aiming at implementing a blockchain prototype for digitalized construction logistics at a large building site. A literature review, undertaken in several iterations from May 2018 to summer 2019 and following the emergence of the hype for blockchain, reveals visions and a few prototypes of related systems for construction. Theoretically, the paper adopts a sociomaterial approach, appreciating that blockchain is as much about social interaction and development of trust, as it is about digitally facilitating economic transactions. Several critical issues threatening to jeopardize the adoption of blockchain are analyzed in the paper, such as the protection of the economic data during transactions, permission access control which only allows a few people to enter the system while still requiring a minimum of trust between those already inside the system, and possible financial speculation on the utilized cryptocurrencies. The way construction stakeholders can mitigate such issues, thus enabling blockchain to become a realized hope rather than harming the sector, is discussed. Probably the largest risk relates to unrealistic hopes of full transparency in open blockchain systems, potentially making the systems too vulnerable to external intervention and even speculation. Permissioned systems with some level of hierarchy appear to be a feasible compromise solution mitigating the potential harm.

Keywords: Blockchain, construction logistics, construction supply chain, security, trust.

1. Introduction

Blockchain, initially conceptualized as the technology underlying bitcoin (Singhal et al., 2018), has been increasingly hyped due to the skyrocketing of business and public interest and investments in digital ledgers, smart contracts and virtual currencies (Wiatt, 2018). In social interaction terms, blockchain is a team technology that facilitates collaboration to counter business challenges; in technical terms, it is a shared, decentralized, and distributed digital ledger replicated across unique nodes representing interacting entities (such as organizations or individuals) (O'Leary, 2017; Penzes, 2018; Singhal et al., 2018; Verhoeven et al., 2018), and can serve as a peer-to-peer value transaction system (O'Leary, 2017; Verhoeven et al., 2018), with no need for the transactions' in-between verification, security and settlement through trusted intermediate third-parties (Singhal et al., 2018; Verhoeven et al., 2018). The database stored on each such digital ledger is append-only, and every new entry is permanent, immutable, and replicated across the nodes (Swan, 2015; Singhal et al., 2018); each new entry is added as a "block" in the chain, it stores a finite set of transaction-related data of a fixed size, and is orderly connected with the previous blocks (Verhoeven et al., 2018). The transaction history follows the chain of blocks, resolves the transactions by holding both the present and the relative historical information, is shared across the nodes, and can only be updated through consensus and validation, utilizing algorithmic methods such as "proof-of-work", "proof-of-stake" and "proof-of-authority" (O'Leary, 2017; Penzes, 2018; Singhal et al., 2018; Verhoeven et al., 2018).

Aside bitcoin, potential applications of blockchain are continuously being investigated; such investigation also points to blockchain's disruptive aspects (Konstantinidis et al., 2018), like its potential as a process performance measurement tool (Kuhi et al., 2018; Ye et al., 2019), and a catalyst for the establishment of a digital ecosystem with the Internet of Things (IoT) (Woodhead et al., 2018). For the construction sector, there has been research on blockchain solutions both for the theoretical understanding and deriving of methodological frameworks on process re-engineering (e.g. see the suggestions in Barima, 2017; Turk & Klinc, 2017; Wang et al., 2017; Kamenetskii & Yas'kova, 2018; and Li et al., 2019b), and for the practical development and implementation of relative applications (e.g. see the applications investigated in Mathews et al., 2017; Wang et al., 2017; Mahmod & Hinton, 2018; Navadkar et al., 2018; Penzes, 2018; Gerber & Nguyen, 2019; and Nguyen et al., 2019).

Among the relative research efforts and focusing on on-site construction logistics and supply chain management, the disintegration of the material and economic flows has been identified as persistent (Shin, Chin, Yoon, & Kwon, 2011), and its potential resolution with the implementation of blockchain has been indicatively investigated, but not systematically in – among others – Wang et al., 2017; Dobrovnik et al., 2018; Lanko et al., 2018; Li et al., 2019b; Penzes, 2018; and Rubio et al., 2018. With the integration of the material and the economic flows through blockchain, a holistic overview of the full construction logistics can be facilitated, through the fostering of trust, transparency and traceability in the relative transactions, enhancing of the deliverables' quality appraisal, facilitation of supply chain stakeholders' collaboration, optimization of constructability (as it is positively impacted by a holistic view on logistics, supply chain integration, and trusted cooperation between stakeholders (Kifokeris & Xenidis, 2017)), and creation of value for the interested parties. Such a creation of value could even formulate new digital business models – namely, digital transformations of the background and processes of organizations in order to create, deliver and capture value (Beck et al. 2017; Konstantinidis et al., 2018).

The creation of such value and its culmination into the relative digital business models tackling the flow disintegration in construction logistics through the use of blockchain, constitute a hope for the construction sector, following the hype with which blockchain solutions are being currently approached. In this paper, and trying to investigate the hands-on realization of such a hope through lessons-learned from other relative examples, a targeted literature review on blockchain-related visions and prototypes for the construction sector, is conducted. However, to also consider issues threatening this realization, thus rendering such a solution a potential form of harm instead of hope, a complementary targeted literature review identifying relative jeopardizing factors, is conducted. For this dual identification, the paper draws on a sociotechnical approach (Orlikowsky, 2016), which entails that the development of digitalization is an intertwined social and technical process, since sociotechnical theories highlight the way technology is co-shaped with practice. Following is the discussion on the research findings and the role of the construction stakeholders in facilitating the realization of the hope and the mitigation of the harm, and the conclusions of the current research effort.

2. Blockchain: a sociomaterial perspective

As mentioned in the introduction, blockchain is a digital technology that can be potentially implemented in a number of building processes in a diverse manner (see, for example, in Barima, 2017; Turk & Klinc, 2017; Penzes, 2018; Gerber & Nguyen, 2019; and Nguyen et al., 2019). However, the largely non-systematic approach on most of these possible implementation efforts reveals that they are largely rather visions, with only a few actual applications leading to working prototypes, which can later lead to the corresponding adoption in use (see, for example, the ones mentioned in Penzes, 2018; Gerber & Nguyen, 2019; and Nguyen et al., 2019). “Vision” refers to the first and the beginning of the second level of the maturity and technology readiness scale for applications (Gerber & Nguyen, 2019), namely “concept” and “demonstration”; “prototype” refers to the completion of the “demonstration” and the commencing of the third level of the scale, namely “commercialization”; and “adoption” refers to the completion of “commercialization”, the final level of the scale, which translates into use in praxis.

To better analyze the gradual embedding and interaction of blockchain in and with building processes and practices, we propose the conversion of the maturity and technology readiness scale into the three aforementioned levels of vision, prototype, and adoption into use. This conversion is compatible with the fact that in the current effort, we mobilize the sociotechnical approach for our research on blockchain for construction in general and building logistics in particular, which entails that the development of digitalization is an intertwined social and technical process (Orlikowsky, 2016). We focus on the sociotechnical approach defined as sociomateriality, which emphasizes the way digital technologies are co-shaped with practices (Bader & Kaiser, 2017; Orlikowsky, 2016). In more detail, from the lens of sociomateriality, the social and the material parts of digital technologies are inseparable (Orlikowsky, 2016). For the particular case of blockchain for building logistics and supply chain management, the sociomaterial scope leads to the perspective that blockchain cannot be understood separately from the building logistics processes themselves, nor their practical realization from vision to prototype and adoption into use. Thus, in this context, the primary unit for blockchain research is not individual entities with well-delimited boundaries and attributes, but rather phenomena materially embedded in practice (Orlikowsky, 2016).

A key aspect of the sociomaterial perspective in the aforementioned context is the discussion on the autonomy-control paradox (Bader & Kaiser, 2017; Zuboff, 2019). While blockchain advocates the claim that the fundamental aspects of the technology itself generate trust and security, it is possibly more sociomaterially precise to understand these generated phenomena as a coexistence of control and autonomy. Blockchain provides overall transparency through generalized and decentralized control, but on the same page, it appears to reduce the autonomy of the single actors represented by the nodes of the blockchain network (Bader & Kaiser, 2017; Zuboff 2019).

3. Blockchain visions and prototypes for construction

As introduced in the first section of the current paper, the integration of the material and the economic flows through blockchain can bring about a holistic overview of the full construction logistics process, through the fostering of trust, transparency and traceability in the transactions within the flows, the enhancing of the deliverables’ quality appraisal, the facilitation of supply chain stakeholders collaboration, the optimization of constructability, and the creation of value for the interested parties – which can then be culminated into new digital business models for the construction supply chain actors implementing such a system. Trying to investigate the hands-on realization of such a hope, we apply a sociomaterial lens in a targeted literature review on blockchain-related visions and prototypes for the construction sector.

In the vision level, Gerber & Nguyen, 2019, and Nguyen et al., 2019, have identified the following market areas and their associated technologies which can be integrated with blockchain solutions to facilitate the corresponding projects and create value for the relative actors:

- Cities – the associated technologies are utilized for the procurement and supply chain management, and the IoT-integrated smart city.
- Energy – the associated technologies are utilized for energy microgrids, electric vehicles' power sharing, smart meter billing, clean energy sources, and renewable certificate tracking and trading.
- Property – the associated technologies are utilized for smart contracts for real estate, title records, lease agreements and automated payments, and property data management.
- Transportation – the associated technologies are utilized for ride hailing, car sharing payments systems, material passports, and biometrics to enable gateless borders.

In Penzes (2018), there have also been identified areas and relative technologies with the potential of hosting integrated blockchain solutions. Some of them, like procurement and supply chain management, corresponded to the ones mentioned above; in addition, other identified areas and technologies included maintenance survey, site management record keeping, smart contract-governed site working hours register and payment systems, design package submissions through smart contracts, on-site health and safety incident registration, and material tracking for improved sustainability. In addition, in Li, Greenwood and Kassem (2019a), a systematic literature review has been conducted on conceptual models and practical use cases regarding blockchain and digital ledger solutions in the built environment, discretized in the areas of smart energy, smart cities / sharing economy, smart government, smart homes, intelligent transport, Building Information Modelling (BIM) in construction management, business models, and organizational structures.

Apart from the cases of visions, there are also certain examples for construction sector-related blockchain solutions that have reached the point of prototype, thus offering a richer understanding on the actual realization of such systems. Notable among such prototypes are the following:

- BIMCHAIN (Mathews et al., 2017; Penzes, 2018; Gerber & Nguyen, 2019, and Nguyen et al., 2019): this prototype is within the market area of cities, and the application areas of BIM coordination and smart asset management. The proponents of BIMCHAIN argue that blockchain can facilitate security, liability, transferability and live data collection; acting as a digital immutable ledger in BIM-supported processes. It allows the project to be mapped and tracked at every stage, thus establishing ownership of models and tracking incremental improvements and changes during the design stage. The related data can be internally and externally controlled and relied upon, increasing transparency and trust, and reducing corruption, inefficiencies, and contractual disputes. To bring about such benefits, BIMCHAIN can act as a legally binding tool, with the aim of high-quality and accountable BIM products. Within BIMCHAIN, smart contracts can be drawn up and payments are automated to ensure that the related actors are committed to achieving their stated outcomes. A market-ready product is expected in 2019.
- Circularise (Gerber & Nguyen, 2019, and Nguyen et al., 2019): this prototype is within the market area of cities, and the application area of circular economy. Within it, blockchain solutions can allow the effective and reliable tracking of materials and components throughout the whole supply chain. Considering the reusability of materials and components as part of their lifecycle, such blockchain-enabled tracking can continue in perpetuity. The manufacturers, recycling agencies, and clients, can consistently and confidently monitor the circularity of their products. In this vein, Circularise, an open and distributed communications protocol, offers an open-source distributed communications protocol for a circular economy, thus allowing information exchange throughout the supply chain and facilitating transparency around product and material histories and destinations.
- SiteSense® (Gerber & Nguyen, 2019, and Nguyen et al., 2019): this prototype is within the market area of cities, and the application area of cash flow construction management. Blockchain can connect all project stakeholders, allowing each actor to track progress and automate payments according to completed work packages. Thus, construction progress can be more effectively monitored, and any cash flow problems mitigated. As a related solution, SiteSense® utilizes blockchain in a cloud-based project site field tool setting to monitor, categorize and maintain relevant resources and documentation. The list of transactions is stored in a private blockchain accessed only by the related stakeholders.
- Blockchain tool for real estate transactions and mortgage deeds (Gerber & Nguyen, 2019, and

Nguyen et al., 2019): this prototype is within the market area of property, and the application area of sale and asset transactions. This tool is piloted by Sweden's land registry authority, Lantmäteriet, and other partners. It connects sellers with real estate agents and buyers and integrates information on land registry and bank accounts. Recent demonstrations of the tool include identifying verification processes, approving and executing digital agreements, and exporting finalized legal contracts. Thus, the process of signing the purchase agreement through the registration of the sale can be facilitated to last only a few days or even hours, instead of four to six months.

- Shipment tracking solution by Maersk and IBM (Gerber & Nguyen, 2019, and Nguyen et al., 2019): this prototype is within the market area of transportation, and the application area of freight tracking and logistics. This venture aims to digitize trading workflows and end-to-end shipment tracking. Within the system, each stakeholder can track the progress of items throughout the supply chain, and check customs documents, bills of lading and other freight data. The role of blockchain is to ensure a secure, well-documented data exchange and transparent repository, and reduce the cost of cumbersome manual paperwork.

The lessons-learned of these visions and especially prototypes for the potential of blockchain-enabled construction logistics with integrated material and economic flows, approached from a sociomaterial angle, will be investigated in the discussion featured later in this paper.

4. Threats to the adoption of blockchain for construction logistics

There can be several jeopardizing factors threatening the adoption of blockchain for construction logistics with integrated economic and material flows. Central among them are the ones regarding the security aspects of blockchain technology itself, which are investigated in Kareem et al., 2018; Penzes, 2018; Sklaroff, 2018; Underwood, 2018; and Veuger, 2018. These threats can be discretized into the following issues: (a) lack of trust of the stakeholders among themselves and in the adoption of blockchain, (b) the disruptive nature of this technology can be viewed with discomfort, and extreme opinions even regard it as a fad, (c) the anonymity of the nodes in the distributed network can lead to illicit activities (e.g. in the purchasing and on-site delivery of material and equipment), (d) the cryptocurrencies used can cause the loss of real-value grasp and can be an object of financial speculation, (e) breaches in the system cryptography can lead to immediate and unrecoverable losses of virtual funds (however unlikely and/or extremely costly in computational means this may be) – as opposed to the potentially retrievable fiat currency funds, and (f) the automated processes can be imbued with such inflexibility that they could even lead to loss rather than creation of value for the stakeholders (e.g. in the case of transactions between the main contractor and the suppliers and subcontractors across the supply chain). Moreover, blockchain is considered by some researchers as ambiguous regarding the value created by implementing the relative solutions – especially for construction logistics – (e.g. in Li et al., 2019b), and as cumbersome to implement without the simultaneous implementation and support of other types of infrastructure as well, such as BIM and IoT (Ye et al., 2019). Many of these threats are also identified in studies of other application areas than construction (Hackius & Petersen, 2018; Khong & Escobar, 2017).

In Penzes (2018), a survey among industry leaders further recognizes barriers in blockchain adoption for construction, divided between early challenges (regulatory uncertainty, lack of trust among users), and obstacles expected to be met in 3-5 years (cost of implementation, question of how to start, and lack of governance). In the same effort, some more dedicated sector-related challenges are identified, such as unmovable organizational vested interests, cultural organizational structures, narrow profit margins, and industry fragmentation. Moreover, Li et al. (2019a) identify as key challenges possibly threatening the adoption of blockchain in the construction industry issues on authentication of data and connectivity, coding of smart contracts, energy consumption of the mining process of proof-of-work blockchain protocols, exchange rate volatility, interoperability, legal constraints, possible malicious attacks, and the industry-wide readiness of adoption and resistance to change. Difficulties in the market adoption of blockchain, misconceptions regarding what it is and how it can be used, and the currently non-existent legal regulations framing its use, are identified by Poszler et al. (2019), as especially detrimental for blockchain implementation for, specifically, logistics and supply chain applications, including the ones related to the construction sector.

Coupled with the challenges are the potential limitations of such an implementation, as identified both during and after the literature review and through discussions with practitioners in the Swedish construction sector. At this point, there is little widespread understanding of the blockchain technology within the construction sector (and especially construction logistics), and the correspondingly dedicated and/or knowledgeable practitioners are few (Barima, 2017; Li et al., 2019a). This can lead to the need of outsourcing the development process of blockchain prototype to blockchain technicians, who may not necessarily be familiar to the particularities of construction logistics. Furthermore, cryptocurrencies may be increasingly accepted for transactions in parts of the construction industry, but they are not accepted by all; and they cannot be avoided in the first place, since they are essential for the function of the blockchain itself. Finally, an always present challenge is the stimulation of the respective actors into adopting a new digital business model utilizing blockchain (Barima, 2017).

5. Discussion: lessons-learned and the role of construction stakeholders

When reviewing the emerging knowledge on blockchain in construction, it is clear that the processes in an around building logistics actually represent a possible field of blockchain implementation, especially for the realization of a solution of blockchain-enabled construction logistics with integrated material and economic flows. However, the lessons-learned from the visions, prototypes, threats and challenges connected to the implementation of blockchain for the construction sector (in general) indicate that a lot of ground has yet to be covered for an actually realized, commercialized and adopted application. The visions are interesting and show potential, but cannot really be assessed until they reach a higher level of technological readiness and maturity; the prototypes may be on track for such a step of development, but most have not reached that just yet; and the threats and challenges still need to be tackled, with some of them being particularly acute in the construction industry (e.g. the low level of knowledge on related technologies among construction-oriented practitioners). Things can be even more tentative for construction logistics in particular, since a business case for the application required to support the implementation of a blockchain system appears to be barely established – if not still absent. The related stakeholders are under these circumstances prone to blocking changes due to a focus on shorter-term impacts (Cooper, 2018).

Therefore, it is crucial to focus on the issue of value creation for all interested parties and stakeholder groups across the supply chain, and to present them with the benefits of blockchain implementation to both themselves and the wider sector (Cooper, 2018). For this, it should be considered that the potential applications may involve more than just agents of the construction industry in specific, as well as different levels or stakeholders within the built environment sector; thus, future work on the development of related blockchain solutions should focus on the value propositions to each stakeholder at each and every phase of the utilization of such a solution (Cooper, 2018). Mapping all stakeholders and interactors within a blockchain-induced solution for construction logistics (especially one seeking to integrate the two main supply chain flows, namely the material and the economic one) and engaging with these groups from the beginning, would optimize the creation and demonstration of the value for each (Cooper, 2018), while also helping to overcome the aforementioned threats and challenges.

The insights mentioned above are in line with the sociomaterial take on the blockchain adoption for construction logistics, as well as the existence of the control-autonomy paradox. For such a perspective, taking as an example the state of the construction sector in Sweden, certain set-ups of stakeholders can be largely identified: (1) large contractors integrating building logistics services internally, to overcome transaction issues and maintain full power over the material supply and economic flows; (2) clients employing small independent logistics consultants to facilitate different interests in the logistics setup, and (3) third-party actors such as construction equipment or industrialized housing suppliers, offering dedicated digital logistics solutions.

These set-ups represent different corresponding business models and forms of collaboration between the participating stakeholders; but rather than viewing these set-ups as technical choices between rational and discernible modes of operation (something recurrent in operations management and business economics), through the sociomaterial approach they are understood as different sociotechnical solutions involving specific distributions of power. The first set-up signifies a more traditional power balance. The second introduces a neutral (in terms of interactions and power distribution) facilitator of the logistics flows; the role of these facilitators is usually signified according to the clients' power and prerogative. The third set-up emanates from strategic moves of companies operating in a field tangential to the construction logistics themselves, and commencing their gaining of influence. In all set-ups, the corresponding operational frameworks are not only influenced by the process of knowledge exchange (Gustavsson, 2018), but also constitute a type of a power and control-autonomy struggle coupled with the considerations of adopting a disrupting digital technology.

Hence, adopting blockchain solutions integrating the material and economic flows within new digital business models for each set-up, should also consider these dimensions and the way they can be addressed by all related stakeholders – and also all the issues emanating from and connecting to those dimensions. In terms of security, for example, large urban construction sites can suffer from theft in material supplies. It is thus underlined that internal trust among participants in a blockchain, in which there is limited or no centralized control, should be facilitated. In this vein, it might be necessary to set up a permissioned access control system and implement a set of processes to protect the blockchain from external threat and mitigate the potential of it constituting a harm. In addition, the issue of integration may involve technical interoperability bottlenecks, changes in work practices and organizational re-engineering. The initial placement of a blockchain solution to integrated building logistics would probably be on top of an information infrastructure consisting of a series of different systems connected to accounting, project planning, quality control, access control, and site planning; then, the adoption of common standards (e.g. for the structuring of digital ledgers), may be in order.

6. Conclusions

Blockchain adoption for construction logistics may bring about optimized ways to tackle problems in the field, especially when discussing solutions integrating the material and economic flows across the construction supply chain as a dimension of a new digital business model – an issue of disintegration that has been identified as recurrent, and the tackling of which could bring about a holistic overview of the full construction logistics process, foster of trust, transparency and traceability in the related transactions, enhance the deliverables' quality appraisal, facilitate the supply chain stakeholders' collaboration, optimize constructability, and create value for the interested parties. Lessons-learned from visions and/or actually operating prototypes of relative solutions in other construction-related contexts – such as urban development, maintenance survey, site management record keeping, smart contract-governed register and payment systems, smart contract-governed design package submissions, on-site health and safety incident registration, material tracking for improved sustainability, smart energy, smart cities and the sharing economy, smart government, smart homes, intelligent transportation, Building Information Modelling and construction management – indicate a strong potential for the adoption of blockchain in construction logistics. However, there are also threats and challenges in such an adoption, like the lack of trust of the stakeholders, speculation on the cryptocurrency value, loss of funds, misconceptions on its use, and ambiguous value creation for the interested stakeholders.

A sociomaterial perspective can help in understanding blockchain's potential, and also the aforementioned challenges and threats, and their coupling with the actual organizational set-ups of the stakeholders collaborating across the supply chain (e.g. contractors encompassing logistics competences, or clients employing third-party logistics consultants). Moreover, it can facilitate the understanding of these matters not only as technical choices between rational and discernible modes of operation, but also as different sociotechnical solutions involving specific distributions of power – something essential when having stakeholders with often conflicting interests, as the ones in construction logistics and supply chain management. By taking these dimensions into account, it can be deduced that the matter of adopting blockchain for construction logistics is something far more complex than just tinkering around a new technological solution. In conclusion, there should be a continuous and significant effort in research, implementation and testing of prototype applications of blockchain solutions for construction logistics (especially when tackling the integration of flows such as the material and economic ones), to reach a point of certainty regarding the feasibility of such solutions. The adoption of a technology as blockchain should be carefully approached, so as it can be realized as a hope for the construction sector, rather than cause harm following a hasty implementation due to the hype surrounding a buzzword.

Acknowledgement

Thanks to Maximiliane Wilkesmann and her colleagues for coining the technology analysis of digitalization in three types; hype, hope or harm (Wilkesmann et al., 2018).

References

Bader, V., & Kaiser, S. (2017). Autonomy and Control? How Heterogeneous Sociomaterial Assemblages Explain Paradoxical Rationalities in the Digital Workplace. Management Revue, 28(3), 338-358. https://doi.org/10.5771/0935-9915-2017-3-338

Barima, O. (2017). Leveraging the blockchain technology to improve construction value delivery: the opportunities, benefits and challenges. In: Construction Projects: Improvement Strategies, Quality Management and Potential Challenges (pp. 93-112). New York: Nova Publishers.

Beck, R., Avital, M., Rossi, M., & Thatcher, J. B. (2017). Blockchain technology in Business and Information Systems Research. Business & Information Systems Engineering, 59(6), 381-384. https://doi.org/10.1007/s12599-017-0505-1

Cooper, H. (2018). Blockchain – feasibility and opportunity assessment. Constructing Excellence delivered with BRE, Report number: 1, issue: 1. Watford: BRE Trust.

Dobrovnik, M., Herold, D.M., Fürst, E., & Kummer, S. (2018). Blockchain for and in Logistics: What to Adopt and Where to Start. Logistics, 2(18), 1-14. https://doi.org/10.3390/logistics2030018

Gerber, D., & Nguyen, B. (2019). Blockchain technology timeline: case studies in the built environment. London: Arup.

Gustavsson, T. K. (2018). Liminal roles in construction project practice: exploring change through the roles of partnering manager, building logistic specialist and BIM coordinator. Construction Management and Economics, 36(11), 599-610. https://doi.org/10.1080/01446193.2018.1464197.

Hackius, N., & Petersen, M. (2017). Blockchain in Logistics and Supply Chain: Trick or Treat? In: Digitalization in Supply Chain Management and Logistics, Proceedings of the Hamburg International Conference of Logistics (HICL). Epubli. https://doi.org/10.15480/882.1444

Kamenetskii, M. I., & Yas'kova, N. Y. (2018). Construction and Real Estate Markets: From Crisis to Growth. Studies on Russian Economic Development, 29(1), 35-40. https://doi.org/10.1134/S1075700718010070

Kareem, A., Sulaiman, R. B., & Farooq, M. U. (2018). Algorithms and Security Concern in Blockchain Technology: A Brief Review. Available online at the Social Science Research Network (SSRN) repository: http://dx.doi.org/10.2139/ssrn.3234933.

Khong, M., & Escobar, M. (2017). New money: are we ready to take on the impacts of a cashless society? A fantasy pitch. Accounting and Management Information Systems, 16(4), 641-647.

Kifokeris, D., & Xenidis, Y. (2017). Constructability: Outline of Past, Present and Future Research. Journal of Construction Engineering and Management, 143(8), 04017035-1 – 04017035-13. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001331

Konstantinidis, I., Siaminos, G., Timplalexis, C., Zervas, P., Peristeras, V. & Decker, S. (2018).

Blockchain for Business Applications: A Systematic Literature Review. In: Abramowicz, W., & Paschke, A. (Eds.). Business Information Systems – 21st International Conference BIS 2018 Proceedings (pp. 384-399). Berlin: Springer. https://doi.org/10.1007/978-3-319-93931-5_28

Kuhi, K., Kaare, K., & Koppel, O. (2018). Ensuring performance measurement integrity in logistics using blockchain. In: 2018 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI) (pp. 256-261). New York: Curran Associates. https://doi.org/10.1109/SOLI.2018.8476737

Lanko, A., Vatin, N., & Kaklauskas, A. (2018). Application of RFID combined with blockchain technology in logistics of construction materials. MATEC Web of Conferences, 170, 03032-1–03032-6. https://doi.org/10.1051/matecconf/201817003032

Li, J., Greenwood, D. J., & Kassem, M. (2019a). Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. Automation in Construction, 102, 288-307. https://doi.org/10.1016/j.autcon.2019.02.005

Li, J., Greenwood, D. J., & Kassem, M. (2019b). Blockchain in the Construction Sector: A Socio-technical Systems Framework for the Construction Industry. In: Mutis, I., & Hartmann, T. (Eds.). Advances in Informatics and Computing in Civil and Construction Engineering (pp. 51-57). Cham: Springer Nature. https://doi.org/10.1007/978-3-030-00220-6_7

Mahmod, R., & Hinton, D. (2018). Blockchain: The Future of the Auditing and Assurance Profession. The Journal of the American Society of Military Comptrollers, 64(1), 23-27.

Mathews, M., Robles, D. & Bowe, B. (2017). BIM+Blockchain: A Solution to the Trust Problem in Collaboration? In: Hore, A., McAuley, B., & West, R. (Eds.). CITA BIM Gathering 2017 (pp. 48-57). Dublin: The Construction IT Alliance.

Navadkar, V. H., Nighot, A., & Wantmure, R. (2018). Overview of blockchain technology in government/public sectors. International Research Journal of Engineering and Technology, 5(6), 2287-2292.

Nguyen, B., Buscher, V., Cavendish, W., Gerber, D., Leung, S., Krzyzaniak, A., Robinson, R., Burgess, J., Proctor, M., O'Grady, K., & Flapper, T. (2019). Blockchain and the Built Environment. London: Arup.

O'Leary, D. E. (2017). Configuring blockchain architectures for transaction information in blockchain consortiums: The case of accounting and supply chain systems. Intelligent Systems in Accounting, Finance and Management, 24(4), 138-147. https://doi.org/10.1002/isaf.1417

Orlikowski, W. J. (2016). Digital Work: A Research Agenda. In: Czarniawska, B. (Ed.). A Research Agenda for Management and Organization Studies (pp. 88-96). Northampton: Edward Elgar Publishing.

Penzes, B. (2018). Blockchain technology in the construction industry: digital transformation for high productivity. London: Institution of Civil Engineers (ICE) Publications.

Poszler, F., Ritter, A. C., & Welpe, I. (2019). Blockchain startups in the logistics industry: The technology´s potential to disrupt business models and supply chains. In: Schröder, M., & Wegner, K. (eds.). Logistik im Wandel der Zeit – Von der Produktionssteuerung zu vernetzten Supply Chains. Wiesbaden: Springer.

Rubio, M. A., Tarazona, G. M., & Contreras, L. (2018). Big Data and Blockchain Basis for Operating a New Archetype of Supply Chain. In: Tan, Y., Shi, Y., Tang, Q. (Eds.). DMBD 2018, LNCS 10943 (pp. 659-669). Springer International Publishing AG. https://doi.org/10.1007/978-3-319-93803-5_62

Shin, T. H., Chin, S., Yoon, S. W., Kwon, S. W. (2011). A service-oriented integrated information framework for RFID/WSN-based intelligent construction supply chain management. Automation in Construction, 20(6), 706-715. https://doi.org/10.1016/j.autcon.2010.12.002

Singhal, D., Dhameja, G., and Panda, P. S. (2018). Beginning Blockchain: A Beginner's Guide to Building Blockchain Solutions. New York: Apress. https://doi.org/10.1007/978-1-4842-3444-0

Sklaroff, J. M. (2018). Smart contracts and the cost of inflexibility. University of Pennsylvania Law Review, 166, 263-303.

Swan, M. (2015). Blockchain: Blueprint for a new economy. Sebastopol: O'Reilly Media.

Turk, Ž., & Klinc, R. (2017). Potentials of Blockchain Technology for Construction Management. Procedia Engineering, 196, 638-645. https://doi.org/10.1016/j.proeng.2017.08.052

Underwood, B. D. (2018). Virtual Market Integrity Initiative Report. New York: Office of the New York State Attorney General.

Verhoeven, P., Sinn, F., and Herden, T. T. (2018). Examples from Blockchain Implementations in Logistics and Supply Chain Management: Exploring the Mindful Use of a New Technology. Logistics, 2, 20-1–20-19. https://doi.org/10.3390/logistics2030020

Veuger, J. (2018). Trust in a viable real estate economy with disruption and blockchain. Facilities, 36(1/2), 103-120. https://doi.org/10.1108/F-11-2017-0106

Wang, J., Wu, P., Wang, X., & Shou, W. (2017). The outlook of blockchain technology for construction engineering management. Frontiers of Engineering Management, 4(1), 67-75. https://doi.org/10.15302/J-FEM-2017006

Wiatt R. G. (2019, January). From the mainframe to the blockchain. Strategic Finance, 100(7), 27-35.

Wilkesmann, M., Steden, S. and Schulz, M. (2018). Industrie 4.0 - Hype, Hope oder Harm? ARBEIT – Zeitschrift für Arbeitsforschung, Arbeitsgestaltung und Arbeitspolitik. 27 (2), 129-150.

Woodhead, R., Stephenson, P., & Morrey, D. (2018). Digital construction: From point solutions to IoT ecosystem. Automation in Construction, 93, 35-46. https://doi.org/10.1016/j.autcon.2018.05.004

Ye, Z., Yin, M., Tang, L., & Jiang, H. (2019). Cup-of-Water theory: A review on the interaction of BIM, IoT and blockchain during the whole building lifecycle. In: ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction (Vol. 35) (pp. 478-486). IAARC Publications Online Repository. https://doi.org/10.22260/ISARC2018/0066

Zuboff, S. (2019). The Age of Surveillance Capitalism: The Fight for a Human Future at the New Frontier of Power. London: PublicAffairs.

Revolutionising AEC financial system within project delivery stages: A permissioned blockchain digitalised framework

Sepehr Abrishami[1, *] and Faris Elghaish[2]

Senior lecturer at University of Portsmouth
Ph.D. Researcher at University of Portsmouth
email: Sepehr.Abrishami@port.ac.uk

Abstract

Extant literature accentuates the potential of blockchain in the Architectural, Engineering, and Construction (AEC) industry, and its prospective to be integrated into the construction projects to automate financial transactions; for better transparency, security, and controlling. Existing research highlights that permissioned blockchain can work as a platform to create a business network among project participants, due to its features being consistent with the construction industry nature. This paper introduces a framework to integrate permissioned blockchain, particularly Hyperledger fabric, into the construction delivery stages. The proposed framework includes specific steps, demonstrating the requirements to build a network within the pre-construction, construction, and closeout stages. Furthermore, the proposed framework reveals the flow of financial transactions throughout the proposed financial system. Due to the Building Information Modelling/Management (BIM) capabilities and cost planning, the proposed framework shows how the integration between blockchain and BIM processes can be achieved. Therefore, the framework identifies the required data from 4D/5D BIM to be entered into the blockchain financial system.

A systematic literature review was used to highlight the advantages of using blockchain in the construction industry, as well as, identifying the appropriate blockchain platform. The framework can be used by industry practitioners to identify the architecture of smart contracts (chaincode) in the construction industry, such as how endorsement and validation policies can be articulated. The outcome of this paper will be used to develop a proof of concept prototype to test and validate the applicability of the proposed conceptual framework through its application to a real case study.

Keywords: BIM, blockchain, AEC, Construction, Hyperledger

1. Introduction

Blockchain is defined as a distributed ledger for the bitcoin cryptocurrency (Swan, 2015), however, through the last few years, blockchain becomes a comprehensive technology to share and record data in high secure platforms (Andoni et al., 2019). Blockchain is widely recommended by many organisations to be exploited to enhance the entire construction projects ((ICE), 2018, Lamb, 2018, Kinnaird et al., 2018). Moreover, blockchain research becomes a trend during the last few years (Turk and Klinc, 2017, Li et al., 2018a). (Mason, 2017, Mason and Escott, 2018) highlighted the importance of implementing specific features of blockchain such as smart contracts to automate payments within the construction industry projects. Further to the researchers' recommendations, AEC companies such as Arup began to declare the high level of interest to integrate blockchain merits within the industry to enhance the construction industry performance in several services, such as automating the payment process, supply chain, and smart cities (Kinnaird et al., 2018). Moreover, BIM becomes a mandatory processes in many countries, and there have been several research to explore the integration of blockchain and BIM, i.e. Mathews et al. (2017) propose the mentioned integration for maximising trust among project participants in AEC industry. Besides, Blockchain and BIM are recommended for building a comprehensive smart milieu—digital built plan— for the construction industry ((ICE), 2018, Lamb, 2018, Kinnaird et al., 2018). Even though, there is a high level of declaration for the importance of blockchain, in terms of payment automation in construction industry, there has not been a real application developed/presented yet.

In this paper, literature review is used to investigate the current state blockchain/smart contracts implementation within the AEC sector, as well as, critically analysing the proposed potentials and the reality of revealed challenges. Thereafter, a conceptual framework will be developed to draw specific steps throughout project delivery stage such as how the blockchain consensus mechanism can be built during pre-construction stage, and how the close-out stage will be totally revolutionised by adopting blockchain.

In this essence, this research is an attempt to move forward the application of blockchain/smart contracts through articulating a conceptual framework, in which, it proposes how the smart contracts can be applied/exploited throughout the entire project delivery stages (Pre-construction, construction and close-out stage). In addition, the proposed framework considered as the interrelationship between the BIM process and the proposed workflow of the automated payment smart contract framework.

2. Overview of Blockchain and smart contracts

Tapscott and Tapscott (2016) define that blockchain is a distributed ledger that records all shared data amongst different members in a network. Each transaction represents a block in the network and subsequently new blocks are linked to previous in order to create a chain (Li et al., 2018b). The interrelationships between all blocks maximise the opportunity of security (Liang et al., 2017). Each block carries a data and hash for previous blocks, which reduce the chance of hacking (Nofer et al., 2017). Li et al. (2018b) mentioned that there are two categorises of Blockchain Networks (BCN), namely, Public BCN which can be accessed by the public, under generic consensus mechanism, and it remains secure due to its cryptography power such as Bitcoins (Andoni et al., 2019); and Consortium BCN, in which, its users should be pre-identified, therefore, the mechanism to get their consensus should be identified clearly and in advance (Li et al., 2018c). Even though, the private BCN represents a single BCN platform for specific organisation with centralised data within the organisation, it is decentralised between the network users.

Peters and Panayi (2016) define smart contract as a platform for enforcing and monitoring the entered data, by trusted source, in the BCN, based on the pre-identified contract terms. Smart contract is a result of evolving BCN ability to transfer cryptocurrency/data over the blockchain throughout the last decade (Christidis and Devetsikiotis, 2016). Andoni et al. (2019) assert that smart contracts uses peer-to-peer (PTP) network that enables multi-trusted parties to manage the data simultaneously, so that each chain in the BCN carries its own data and subsequently all data will be stored in the ledger according to agreed consensus mechanism (Watanabe et al., 2016). Additionally, smart contracts reduce the dependency on lawyers/ third persons in executing and monitoring the contract terms such as financial transaction, therefore, the accuracy and transparency of data could be enhanced (Mason and Escott, 2018). That is why, Christidis and Devetsikiotis (2016) contend that smart contracts gives an advantage for the user to have an automatic audit to the transferred data, as well as, once the data is valid, will be immutable which enhance the transparency and security. There are several platforms to develop a blockchain platform that smart contracts can be developed and integrated into the network. The most well-known platform is the Ethereum smart contract, which is a decentralised platform in cloud 2.0, where the data (i.e. Payments, penalties) can be shared (Wood, 2014). The process runs on Ethereum Virtual Machine (EVM) and can generate multi-smart contracts with the same characteristics (Hildenbrandt et al., 2017), therefore, there are the data sender and the petitioner. The shared information should be checked automatically to ensure there is no corrupted data, impartial payment, and etc. (Liu et al., 2018). Moreover, in smart contracts, it is ensured that the shared data, as business codes and information between different departments in an organisation, can be recorded confidently and protected from the competitors (Nakasumi, 2017), and each transaction requires an acceptance from the network core members in order to reach consensus (Andoni et al., 2019). Since Distributed ledger relies on cryptocurrencies, the linking between blockchain and traditional bank accounts is considered as a part of the fourth industrial revolution (Mason, 2017).

There are two types of blockchain, namely, Permissionless and Permissioned (Wüst and Gervais, 2018). The permissionless blockchain allows anonymous users to act in the blockchain and add new transaction based on generic consensus mechanism, such as Proof of Work (PoW) (Cachin, 2016). In permissioned blockchain participants are known, vetted and includes a governance approach that regulates the relationships among participants, which maximise the trust (Vukolić, 2017). Since all entities are well-defined in the chain, the permissioned blockchain can use consensus models such as crash fault tolerant (CFT) or byzantine fault tolerant (BFT), as the malicious opportunities are diminished (Baliga, 2017, Cachin, 2016).

According to Androulaki et al. (2018), the smart contract in hyperledger is called chaincode, which can be written in different programming language such as GO and Java script (Cachin, 2016). The program could be articulated separately and using API to interact with the blockchain (Androulaki et al., 2017). The user interacts with multiple nodes simultaneously through a channel, to create a business layer software development process (Vukolić, 2016). In any organisation, the channel could be used to share specific information to specific node, which keep the information private (Cachin, 2016). Transaction management is the philosophy of splitting transaction logs and the ordering process; thus, this allows to perform parallel transaction concurrently. Therefore, the ordering will be solely implemented for endorsing transactions (Androulaki et al., 2018).

Dhillon et al. (2017) and Hyperledger (2018) state that blockchain network comprises of several peer nodes, and each peer node includes different smart contracts and ledgers. The application is used to propose the transaction to perform a smart contract, thus, the proposed smart contract after the validation will be recorded in a specific ledger (Androulaki et al., 2018, Vukolić, 2016). In order to link mutual smart contracts for different peer nodes, a channel is used to send the proposed transaction as well as reflecting the response to the application (Benhamouda et al., 2018). The order of transaction is a pivotal task to package multiple transactions in a single block, and subsequently, record the block to its peer node (Dhillon et al., 2017, Hyperledger, 2018).

Xu et al. (2017) defines Consensus mechanism as a set of rules (algorithms) to ensure the correctness of performing set of transactions through a blockchain network. These specific algorithms are unified within a single function, and the consensus mechanism is responsible to order the transaction, check its validity via different endorsers, and allocate validated transaction to their ledger (Androulaki et al., 2018, Hyperledger, 2018). There are two main properties, namely, safety and liveness (Cachin and Vukolić, 2017, Hyperledger, 2018). Existing smart contracts use order-execute architecture, that requires all nodes to validate and execute every transaction, and the consensus should be completely identified/agreed upon (Androulaki et al., 2018).

In this essence, hyperledger works based on modular environment, which includes a pluggable consensus mechanism, management process, ordering approach, chaincode, and membership service (Androulaki et al., 2018, Benhamouda et al., 2018, Cachin, 2016). Therefore, each organisation could acclimatise the hyperledger in accordance with its hierarchy of data sharing, and the hyperledger can be configured by multiple users to provide a flexible platform for different industry purposes (Hyperledger, 2018).

Klaokliang et al. (2018) mentions the structure of hyperledger fabric comprises of (1) **Ledger**, which is a set of blocks that records multiple transactions, (2) **Peer**, that is a pool containing ledgers and smart contracts, (3) **Chaincode** is the smart contract to perform transaction according to the hyperledger concept, (4) **Channel**, which it is the path that the transaction and blocks take to be allocated amongst different peers, (5) **Endorsement policy**, which is a set of instructions that provide specific metrics to the peer to decide whether the received transaction valid or invalid (Hyperledger, 2018), (6) **Ordering service,** which is a node (Ordering Service Node (OSN)) that is exploited to order the transactions and blocks based on the agreed consensus mechanism, such as Kafka. This node should include specific information regarding the size of blocks, maximum time, and number of allowed transaction for each block before assigning it to the peer through the channel (Androulaki et al., 2018, Hyperledger, 2018).

Implications of blockchain/smart contracts in the construction industry:

Despite Blockchain does not creep into the construction industry like some other technologies, there are several attempts to adopt it by emerging business models (Tozzi, 2018), as an instance, Bimchain is a proof of concept to integrate BIM into Blockchain as a plug-in into the BIM platforms (Bimchain, 2018, Lamb, 2018). Fox (2019) states that there are several benefits of adopting smart contracts in the construction industry, such as; delivering the agreed contracts automatically with enabling parties to update any variations, enhancing the copyright for the project documentations, automated payments amongst project parties, and potentially it can works as a claim submission platform (Lamb, 2018, Tozzi, 2018). As such, smart contracts will be valuable, in terms of automation of some construction processes that traditionally relies on multi-interactions and contribution from project participants to make a decision (Mason, 2017, Mason and Escott, 2018).

Uncertainties in construction payments are a challenge in developing reliable cash flow and subsequently leads to several claims that affect the business growing (Carmichael and Balatbat, 2010, Elghaish et al., 2019). Since the construction trust account is recommended (Cardeira, 2015), Smart contracts can work as a trust account that hold the money and transferred automatically to the party who warranted it (Cardeira, 2015). That is because, the project participants will trust the smart contracts outputs, as all embedded data is immutable and decentralised (Christidis and Devetsikiotis, 2016, Lamb, 2018, Mason and Escott, 2018, Watanabe et al., 2016).

Koutsogiannis and Berntsen (2019) argue that digital construction is an integrated process, thus when a building's real-time digital will be implemented, the smart contracts will be more effective and applicable. Exploiting smart contracts with cryptocurrencies supports articulating a contract draft that specific funds can be embedded to avoid the common insolvency issues or late payment in the construction industry (Cardeira, 2015). In addition, the cross verifications by several references lead to acquiring an efficient, robust, secure and reliable system, which build a trust environment amid project parties (Mason, 2017, Mason and Escott, 2018).

3. Previous research on blockchain and Smart contracts in Construction Industry:

Through using Scopus, Web of Since (WoS) and google scholar research repository, researchers have used relevant keywords to find the relevant papers in implementing blockchain and smart contracts in the construction industry/built environment. The used keywords were, namely; "blockchain in construction" and "blockchain and smart contracts in built environment". The output of the search was 13 papers, the table below shows the contribution of each paper to raise the awareness of implementing blockchain and smart contracts in the construction industry, whether thorough addressing it directly or indirectly in different disciplines.

Table 1. Previous research in the field: Analysis of core drivers

Discipline	Contributions	Authors
Construction management and built environment	• Highlighting the potential of blockchain in construction management, as well as providing a map to direct potential users to select the suitable type of blockchain based on the nature of the data and the hierarchy of the organisation. • Illustrating the blockchain interoperability with other systems (data storage)	Turk and Klinc (2017)
	• Highlighting the challenges that face implementing smart contracts in the construction industry. • Articulate specific steps that should be considered by industry participants.	Mason and Escott (2018)
	• Providing an emergent framework that considers multi-dimensions, namely social, political and technical. This is in order to enable potential developers/users of blockchain in construction to highlight the potentials and challenges.	Li et al. (2019b) and Li et al. (2018a)
	• Asserting the importance of intelligent contract (smart) for the construction industry through saving the cost of	Mason (2017)

	employing third party. And, minimising needed time to perform new transactions. • Highlighting the importance of integrating smart contracts into BIM in order to automate the construction process.	
	• Presenting an outlook for implementing blockchain to revolutionize the persist issues in managing the supply chain, contract management and resource management, particularly leasing equipment. • Providing a taxonomy of blockchain implementation challenges in the AEC industry.	Wang et al. (2017)
	• Linking the current challenges that face construction industry to the potential benefits of blockchain to provide reliable solutions. • Researchers articulated a framework—Presenting the socio-technical dimensions— this could facilitate implementing blockchain in seven areas of the built environment as categorised by researchers. • Identifying decision making criteria in terms of adopting blockchain.	Li et al. (2019a)
Blockchain and Internet of Things	• Providing a model to show the possibility of integrating Blockchain into IoT and highlighting the potentials of this integration. • Further with the mentioned model, the authors present a detailed list of blockchain usages in different sectors. Moreover, authors underpin the new concepts of chain of things, and blockchain of things.	Reyna et al. (2018)
	• Authors articulated a decentralised blockchain based supply chain management model to overcome the current challenges of supply chain. • The proposed Supply chain via blockchain MAS uses the smart contracts into blockchain.	Casado-Vara et al. (2018)
	• Pointing out the benefits of blockchain and IoT to support a shared economy such as Uber. • Presenting examples of shared economy applications such as AutoPay, which is used to pay car parking fee.	Huckle et al. (2016)
Data movement in the Energy sector	• Highlighting the potential benefits of using blockchain in the energy sector, such as price discovery, logistics, identify customers, reconcile any problem and reporting it. • Presenting a MicroGrid based blockchain to manage and control energy demands.	Andoni et al. (2019)
Generic application of blockchain and smart contracts	• Providing a study map to point out the needed future research to implement blockchain and smart contracts. • The authors concluded (n=16) issues in implementing smart contracts. Therefore, the findings of this paper could be used by researchers and developers to try to find remedies for mentioned problems.	Macrinici et al. (2018)

4. Methodology:

Since, structured literature review is highly recommended to draw a comprehensive understanding about a specific topic, on other words, a literature review should be concept-centric (Webster and Watson, 2002). Langley (1999) states that “review articles may draw from both variance and process research to develop conceptual models to guide future”. Thus, the literature review is utilised to define the research gap and explore all possible solutions to approach/fill the revealed gaps, in terms of previous attempts to adopt blockchain (automated payment) in the construction industry, as well as, existing recommendations/directions to exploit the blockchain potential in different industries. (Gregory and Watson, 2008). Afterwards, a conceptual framework will be developed to provide robust solutions regarding implementing smart contracts, in terms of the automated payment, throughout the entire construction delivery stages.

4.1. Development Framework:

The construction process comprises of three main stages, namely; pre-construction, construction, and closeout. Throughout all mentioned stages, there are a huge number of transactions of moving information among project participants, which requires a platform to record all these data, particularly the payment transactions between the owner and non-owner parties. Since BIM became mandatory in the UK, the needed payment platform should be compatible and interoperable with BIM process/applications. The extant literature review demonstrates the blockchain’s ability to record the transaction and make it immutable. Therefore, the blockchain is adopted to develop an automated platform to automate the payment between project participants. The mechanism of using this platform is designed to be workable in parallel with the construction stages.

4.2. Pre-construction stage:

Throughout the pre-construction stages, the parties agree upon the project contractual conditions that include the mechanism of payments, retentions, etc. These conditions will be coded in order to be used as a validation data in blockchain platform, the validation process is called consensus mechanism, which is defined as a set of algorithms to ensure the validity of invoked and recorded data on the blockchain network (Baliga, 2017, Cachin and Vukolić, 2017, Wang et al., 2018). As critically discussed in the literature review, permissioned blockchain must fits with the construction context due to its ability to limit the adversarial consequences of general blockchain, such as the privacy, private membership and legality of the network, accordingly, a privileged party should be appointed to allocate the responsibilities and roles during using the blockchain platform (i.e. data sender and receiver). Thereafter, the consensus mechanism should be agreed by all parties before deploying the blockchain (construction process). Since the permissioned blockchain has pre-defined counterparts, which requires an automated consensus mechanism, this mechanism should include a quantified data that can work as validation points to automate the consensus mechanism. Once the construction process begins, the blockchain developer can deploy it, and it can be used to share the information, particularly the payment data. BIM can play a significant role in this stage through providing the proposed prices for each package (5D BIM) and linking these prices to the timeline (4D BIM) in order to provide constant payment milestones for all non-owner parties.

4.3. Construction stage

During the construction process, the privileged party could start to assign who is the data sender/receiver at each payment milestone. Similar to the conventional financial system in the construction industry, the contractor works as a data sender (i.e. invoice), and the client representative could be the data receiver. Therefore, the endorsement policy should include the client and architect as the main endorser for any invoked transaction, and this should be listed in the generic endorsement policy (i.e. Hyperledger fabric's consensus mechanism relies on two stages to validate the transaction, first is the endorsement policy that includes who should accept the transaction, and the second stage is the data-blocks allocation through specific channel as described in the theoretical background section). The agreed consensus mechanism will be applied to each block (transaction) automatically, to check its validity based on agreed terms and conditions, such as payment timeline and maximum value of each invoice. Therefore, once the transaction is validated, the data will be sent to the parties' ledger. On the contrary, if the sent data is invalid (whether by the consensus mechanism or the receiver) the privileged person (voter) check the nature of the transaction and explore the source of invalidity, subsequently, insert the transaction again as a new block, which should meet all consensus criteria and pass through the same process. One of the most important advantage of blockchain is the internal validation amongst blocks themselves, that enable automated checking of the sequence of payments between all parties. For instance, one party could act as a data sender for several times during the construction process, so all recorded transactions could be identified and check each other, so not to exceed the maximum value of the contract and inform the parties about any significant cost overrun for any party.

Concerning BIM role in the construction stage with blockchain, the contractor (Data sender) should check the production output against planned (4D and 5D BIM) to prepare the invoice values and obtain the deserved value. Whilst, the client representative uses BIM to check the invoice value. Since all the data are centralised in the federated BIM model, it enables all parties to obtain the same information at the same time.

In permissioned blockchain, the privileged party is able to make some parties silent once their work has been accomplished, and parties can follow the progress of the project from different geographical locations. This confirms the ability of blockchain to support the future of collaborative delivery approaches, such as Integrated Project Delivery (IPD), so that the party is not necessarily available throughout the entire project timeline but can follow all progress through checking all new blocks in the blockchain. The silent parties will be able to check the uploaded data on the Common Data Environment (CDE) to raise the degree of transparency between all parties. As such, the entered data into blockchain could be checked whether using federated BIM model by parties or by the client representative.

4.4. Close out stage

Once the project is completed, the blockchain can play a key role in closeout stage as the inherent issue in preparing the historical cost data for the construction projects. Even though using blockchain enables users to export all recorded data, the client can evaluate all parties' progress throughout the construction process, in order to have a clear vision regarding selecting future parties in new projects. As such, the owner and non-owner parties get several benefits of the final output of blockchain during the close out stage, so that the owner can evaluate other parties and non-owner parties can follow their remaining rights, such as receiving their accumulative retentions, which can be highlighted on the blockchain records to enable detecting the monetary values.

To conclude the mechanism of the proposed framework, it is an automated platform to receive, validate, record and display immutable payments data throughout the entire construction process, once the block becomes valid, it cannot be amended, therefore, all non-owner parties' rights will be kept, which potentially reduces the payment claims. Regarding receiving the remaining rights for non-owner parties after handing the project, such as receiving retention money, the blockchain remains active to send a request based on recorded retention values, and the once the client accepts these values, it will be transferred directly to their accounts. Moreover, the proposed framework enhances the estimation process in the future projects, through providing a reliable historical cost data. As such, the cost data will be sustainable inside the consortium or the business organisation.

4.5. Model interoperability

Figure (1) shows the tasks that should be implemented at each stage. The ordered tasks could facilitate the implementation process; therefore, it can be used as a departure point for the industry user in terms of determining needed resources and capabilities to employ permissioned blockchain. BIM conceptually embedded into the proposed blockchain adoption process in order to build a robust and applicable proposal.

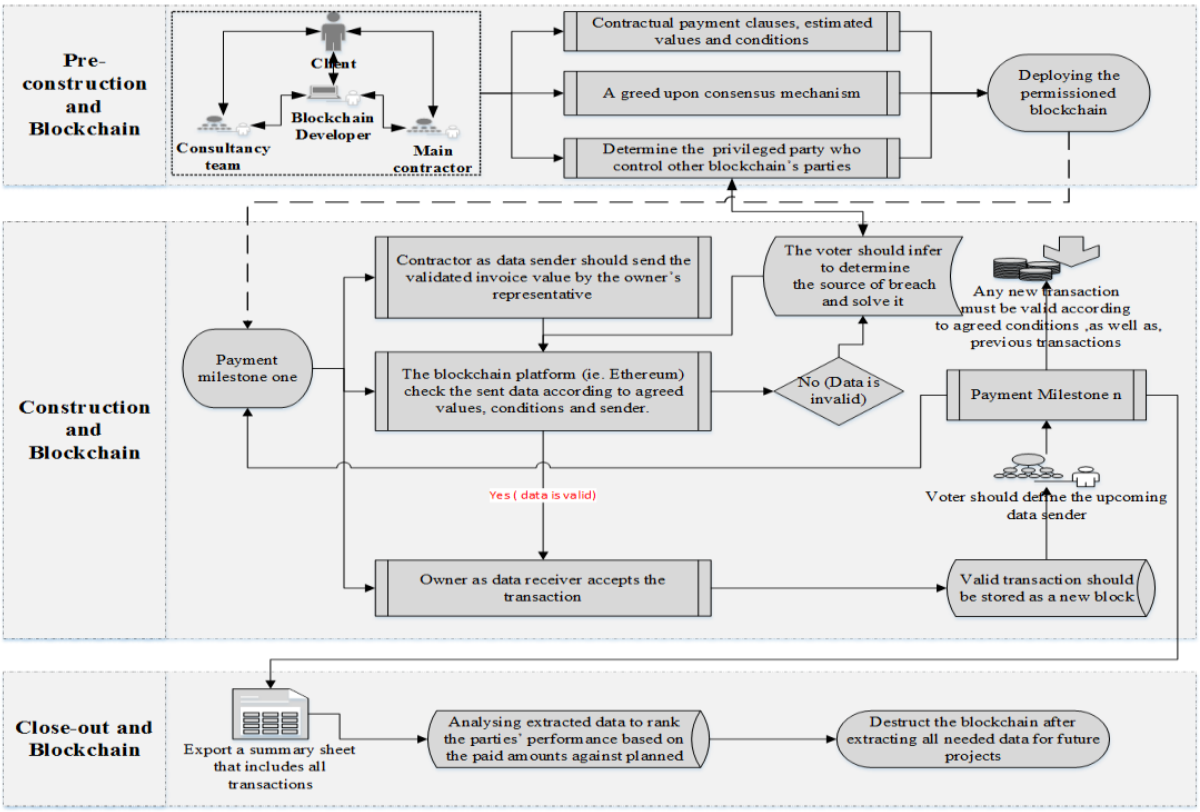


Figure 1. The automated payment conceptual framework

5. Research significance and conclusion

From the literature review survey, the hyperledger fabric is the most suitable blockchain platform to automate the payment through the entire construction delivery stages, that is because; (1) its consensus mechanism is modular that enables project parties to build a consistent mechanism according to the project conditions (Androulaki et al., 2018, Brandenburger et al., 2018, Dhillon et al., 2017), (2) the applicability due to the several cooperation between hyperledger (Linux), IBM, Oracle and SAP, which facilitates its implementation (Van Mölken, 2018, Vukolić, 2016).

Through critical analysis of the previous researches in blockchain within the AEC industry, most of these researches focused on building a theoretical foundation that can be used as a departure point in order to move forward the application, or developing prototypes to validate proposed researchers' themes and conceptual frameworks.

As such, this research is an attempt to draw a realistic application to smart contracts through defining the requirements before the construction stage such as building the consensus mechanism. In addition, the construction stage has been carefully considered within the proposed framework, and the flow of data is highlighted (i.e. who is the data sender and receiver). The closeout stage is not enough investigated regarding financial issues (Kiprotich, 2014), and most claims raised at this stage, thus, the proposed framework includes a list of tasks that should be implemented with smart contracts, whether minimising potential claims, or to be used as a mean to resolve the disputes. This could come to the reality through exploiting the functionality of smart contracts in order to add more functions and to record all types of financial issues (i.e. advanced payments, regular payments and retentions).

References

(ICE), I. O. C. E. 2018. BLOCKCHAIN TECHNOLOGY IN THE CONSTRUCTION INDUSTRY Digital Transformation for High Productivity.

ANDONI, M., ROBU, V., FLYNN, D., ABRAM, S., GEACH, D., JENKINS, D., MCCALLUM, P. & PEACOCK, A. 2019. Blockchain technology in the energy sector: A systematic review of challenges and opportunities. *Renewable and Sustainable Energy Reviews,* 100**,** 143-174.

ANDROULAKI, E., BARGER, A., BORTNIKOV, V., CACHIN, C., CHRISTIDIS, K., DE CARO, A., ENYEART, D., FERRIS, C., LAVENTMAN, G. & MANEVICH, Y. Year. Hyperledger fabric: a distributed operating system for permissioned blockchains. *In:* Proceedings of the Thirteenth EuroSys Conference, 2018. ACM, 30.

ANDROULAKI, E., CACHIN, C., DE CARO, A., KIND, A. & OSBORNE, M. Year. Cryptography and protocols in hyperledger fabric. *In:* Real-World Cryptography Conference, 2017.

BALIGA, A. 2017. Understanding blockchain consensus models. *Persistent.*

BENHAMOUDA, F., HALEVI, S. & HALEVI, T. Year. Supporting private data on Hyperledger Fabric with secure multiparty computation. *In:* 2018 IEEE International Conference on Cloud Engineering (IC2E), 2018. IEEE, 357-363.

BIMCHAIN. 2018. *Accelerating BIM through the Blockchain* [Online]. Available: https://bimchain.io/ [Accessed 14/04/2019 2019].

BRANDENBURGER, M., CACHIN, C., KAPITZA, R. & SORNIOTTI, A. 2018. Blockchain and trusted computing: Problems, pitfalls, and a solution for hyperledger fabric. *arXiv preprint arXiv:1805.08541*.

CACHIN, C. Year. Architecture of the hyperledger blockchain fabric. *In:* Workshop on distributed cryptocurrencies and consensus ledgers, 2016.

CACHIN, C. & VUKOLIĆ, M. 2017. Blockchain consensus protocols in the wild. *arXiv preprint arXiv:1707.01873*.

CARDEIRA, H. 2015. Smart contracts and their applications in the construction industry. Romanian Construction Law Review.

CARMICHAEL, D. G. & BALATBAT, M. C. 2010. A contractor's analysis of the likelihood of payment of claims. *Journal of Financial Management of Property and Construction,* 15**,** 102-117.

CASADO-VARA, R., PRIETO, J., DE LA PRIETA, F. & CORCHADO, J. M. 2018. How blockchain improves the supply chain: Case study alimentary supply chain. *Procedia computer science,* 134**,** 393-398.

CHRISTIDIS, K. & DEVETSIKIOTIS, M. 2016. Blockchains and smart contracts for the internet of things. *Ieee Access,* 4**,** 2292-2303.

CUCCURU, P. 2017. Beyond bitcoin: an early overview on smart contracts. *International Journal of Law and Information Technology,* 25**,** 179-195.

DHILLON, V., METCALF, D. & HOOPER, M. 2017. The hyperledger project. *Blockchain enabled applications.* Springer.

ELGHAISH, F., ABRISHAMI, S., ABU SAMRA, S., GATERELL, M., HOSSEINI, M. R. & WISE, R. 2019. Cash flow system development framework within integrated project delivery (IPD) using BIM tools. *International Journal of Construction Management*, 1-16.

FOX, S. 2019. *Why construction needs smart contracts* [Online]. https://www.thenbs.com/knowledge/why-construction-needs-smart-contracts. [Accessed 13/04/2019 2019].

GREGORY, A. & WATSON, T. 2008. Defining the gap between research and practice in public relations programme evaluation–towards a new research agenda. *Journal of Marketing Communications,* 14**,** 337-350.

HILDENBRANDT, E., SAXENA, M., ZHU, X., RODRIGUES, N., DAIAN, P., GUTH, D. & ROSU, G. 2017. Kevm: A complete semantics of the ethereum virtual machine.

HUCKLE, S., BHATTACHARYA, R., WHITE, M. & BELOFF, N. 2016. Internet of things, blockchain and shared economy applications. *Procedia computer science,* 98**,** 461-466.

HYPERLEDGER. 2018. *A Blockchain Platform for the Enterprise (Transaction Flow)* [Online]. Available: https://hyperledger-fabric.readthedocs.io/en/release-1.3/txflow.html [Accessed 2019].

KINNAIRD, C., GEIPEL, M. & BEW, M. 2018. Blockchain technology: how the inventions behind bitcoin are enabling a network of trust for the built environment.

KIPROTICH, C. J. K. 2014. *An investigation on Building Information Modelling in Project Management: challenges, strategy and prospects in the Gauteng Construction Industry, South Africa.*

KLAOKLIANG, N., TEAWTIM, P., AIMTONGKHAM, P., SO-IN, C. & NIRUNTASUKRAT, A. Year. A novel IoT authorization architecture on hyperledger fabric with optimal consensus using genetic algorithm. *In:* 2018 Seventh ICT International Student Project Conference (ICT-ISPC), 2018. IEEE, 1-5.

KOUTSOGIANNIS, A. & BERNTSEN, N. 2019. *Blockchain and construction: the how, why and when* [Online]. Available: http://www.bimplus.co.uk/people/blockchain-and-construction-how-why-and-when/ [Accessed 14/04/2019 2019].

LAMB, K. 2018. Blockchain and Smart Contracts: What the AEC sector needs to know.

LANGLEY, A. 1999. Strategies for theorizing from process data. *Academy of Management review,* 24**,** 691-710.

LI, J., GREENWOOD, D. & KASSEM, M. Year. Blockchain in the built environment: analysing current applications and developing an emergent framework. *In*, 2018a. Diamond Congress Ltd.

LI, J., GREENWOOD, D. & KASSEM, M. 2019a. Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in Construction,* 102**,** 288-307.

LI, J., GREENWOOD, D. & KASSEM, M. 2019b. Blockchain in the construction sector: a socio-technical systems framework for the construction industry. *Advances in Informatics and Computing in Civil and Construction Engineering.* Springer.

LI, Z., BARENJI, A. V. & HUANG, G. Q. 2018b. Toward a blockchain cloud manufacturing system as a peer to peer distributed network platform. *Robotics and Computer-Integrated Manufacturing,* 54**,** 133-144.

LI, Z., KANG, J., YU, R., YE, D., DENG, Q. & ZHANG, Y. 2018c. Consortium blockchain for secure energy trading in industrial internet of things. *IEEE transactions on industrial informatics,* 14**,** 3690-3700.

LIANG, X., SHETTY, S., TOSH, D., KAMHOUA, C., KWIAT, K. & NJILLA, L. Year. Provchain: A blockchain-based data provenance architecture in cloud environment with enhanced privacy and availability. *In:* Proceedings of the 17th IEEE/ACM international symposium on cluster, cloud and grid computing, 2017. IEEE Press, 468-477.

LIU, K., DESAI, H., KAGAL, L. & KANTARCIOGLU, M. 2018. Enforceable Data Sharing Agreements Using Smart Contracts. *arXiv preprint arXiv:1804.10645*.

MACRINICI, D., CARTOFEANU, C. & GAO, S. 2018. Smart contract applications within blockchain technology: A systematic mapping study. *Telematics and Informatics*.

MASON, J. 2017. Intelligent contracts and the construction industry. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction,* 9**,** 04517012.

MASON, J. & ESCOTT, H. Year. Smart contracts in construction: views and perceptions of stakeholders. *In:* Proceedings of FIG Conference, Istanbul May 2018, 2018. FIG.

MATHEWS, M., ROBLES, D. & BOWE, B. 2017. BIM+ blockchain: A solution to the trust problem in collaboration?

NAKASUMI, M. Year. Information sharing for supply chain management based on block chain technology. *In:* 2017 IEEE 19th Conference on Business Informatics (CBI), 2017. IEEE, 140-149.

NOFER, M., GOMBER, P., HINZ, O. & SCHIERECK, D. 2017. Blockchain. *Business & Information Systems Engineering,* 59**,** 183-187.

PETERS, G. W. & PANAYI, E. 2016. Understanding modern banking ledgers through blockchain technologies: Future of transaction processing and smart contracts on the internet of money. *Banking beyond banks and money.* Springer.

REYNA, A., MARTÍN, C., CHEN, J., SOLER, E. & DÍAZ, M. 2018. On blockchain and its integration with IoT. Challenges and opportunities. *Future Generation Computer Systems,* 88**,** 173-190.

SWAN, M. 2015. *Blockchain: Blueprint for a new economy*, " O'Reilly Media, Inc.".

TAPSCOTT, D. & TAPSCOTT, A. 2016. *Blockchain revolution: how the technology behind bitcoin is changing money, business, and the world*, Penguin.

TOZZI, C. 2018. *How Blockchain Innovation Can Help Cost-Efficiency in the Construction Industry* [Online]. Available: https://www.nasdaq.com/article/how-blockchain-innovation-can-help-cost-efficiency-in-the-construction-industry-cm956525 [Accessed 2019 14/04/2019].

TURK, Ž. & KLINC, R. 2017. Potentials of blockchain technology for construction management. *Procedia engineering,* 196**,** 638-645.

VAN MÖLKEN, R. 2018. *Blockchain across Oracle: Understand the details and implications of the Blockchain for Oracle developers and customers*, Packt Publishing Ltd.

VUKOLIĆ, M. 2016. Hyperledger fabric: towards scalable blockchain for business. Tech. rep. Trust in Digital Life 2016. IBM Research, 2016. URl: https://www ….

VUKOLIĆ, M. Year. Rethinking permissioned blockchains. *In:* Proceedings of the ACM Workshop on Blockchain, Cryptocurrencies and Contracts, 2017. ACM, 3-7.

WANG, J., WU, P., WANG, X. & SHOU, W. 2017. The outlook of blockchain technology for construction engineering management. *Frontiers of engineering management*, 4**,** 67-75.

WANG, W., HOANG, D. T., XIONG, Z., NIYATO, D., WANG, P., HU, P. & WEN, Y. 2018. A survey on consensus mechanisms and mining management in blockchain networks. *arXiv preprint arXiv:1805.02707*.

WATANABE, H., FUJIMURA, S., NAKADAIRA, A., MIYAZAKI, Y., AKUTSU, A. & KISHIGAMI, J. Year. Blockchain contract: Securing a blockchain applied to smart contracts. *In:* 2016 IEEE International Conference on Consumer Electronics (ICCE), 2016. IEEE, 467-468.

WEBSTER, J. & WATSON, R. T. 2002. Analyzing the past to prepare for the future: Writing a literature review. *MIS quarterly***,** xiii-xxiii.

WOOD, G. 2014. Ethereum: A secure decentralised generalised transaction ledger. *Ethereum project yellow paper*, 151**,** 1-32.

WÜST, K. & GERVAIS, A. Year. Do you need a Blockchain? *In:* 2018 Crypto Valley Conference on Blockchain Technology (CVCBT), 2018. IEEE, 45-54.

XU, X., WEBER, I., STAPLES, M., ZHU, L., BOSCH, J., BASS, L., PAUTASSO, C. & RIMBA, P. Year. A taxonomy of blockchain-based systems for architecture design. *In:* 2017 IEEE.

Towards a Cyber-Physical Postural Training System for Construction Workers

Abiola Akanmu[1*] and Johnson Olayiwola[2]
[1,2] Myers Lawson School of Construction, Virginia Tech, Blacksburg, VA, USA
* email: abiola@vt.edu

Abstract

The construction industry continuously struggles with productivity loss and premature exits of workers from the workforce. This has been partly attributed to the physically demanding and repetitive nature of construction tasks, which results in workers assuming unsafe postures. Execution of construction work in unsafe postures leads to strain on the body segments, which results in fatigue, injuries or in severe cases, permanent disabilities. One way of mitigating the occurrences of these injuries is by adequately training workers to make them aware of appropriate postures for executing construction tasks. Existing education or training methods have been largely based on online manuals and instructor-led trainings, which do not provide construction workers opportunities to try-out the trainings and obtain feedback based on their performance. Moreover, trying out these trainings on actual job-sites with direct supervision by the ergonomic experts can be disruptive to on-going projects, costly, and time-consuming. Virtual reality offers the option to produce and distribute analogous simulation environments in which workers' performance can be measured and improved. When integrated with wearable sensors, ergonomic exposures of different body segments can be captured and assessed via an intelligent virtual instructor, providing immediate feedback and coaching to improve worker's motor skills in working in safe postures. This paper presents a framework of a cyber-physical postural tracking and feedback system that leverages virtual reality and wearable sensors for educating construction workers about the risks associated with their work and suggesting alternative motions and postures. The virtual environment of the proposed framework consists of an intelligent virtual instructor which comprises of learning scenarios and intelligent feedback and recommendation system. The virtual instructor is capable of diagnosing knowledge and skill gaps of individual workers in achieving optimal work behaviors and adapting instructional contents and delivery methods according to the need of individual trainees. The framework was developed and preliminary results indicate that the proposed immersive learning technology would improve safe postural learning. Significant implications for future experimental and postural correction protocols are also discussed.

Keywords: Postural Training, Virtual Reality, Wearable Sensors, Machine Learning and Cyber-physical systems

1. Introduction

Musculoskeletal injuries are a growing concern for the construction industry. The United States' Bureau of Labor Statistics (BLS) reports that work-related musculoskeletal disorders (WMSDs) make up nearly 40% of all injuries and illnesses requiring days away from work in the construction industry ((BLS), 2018). This has also been linked to significant productivity and economic loss. For example, according to a 2018 report by Liberty Insurance, direct workers' compensation costs due to musculoskeletal disorders amounted to about $19 billion (Insurance, 2018). The National Institute for Occupational Safety and Health identified awkward working postures as one of the triggers of musculoskeletal injuries (Bernard & Putz-Anderson, 1997). Awkward postures are body positions that deviate from the neutral posture such as performing bending or twisting to lift, overhead work, stooping and squatting (Talk, 2015). Performing activities in awkward postures put a lot of strain and fatigue most commonly on the back, knee, and neck/shoulders (Salas, Vi, Reider, & Moore, 2016; D. Wang, Dai, & Ning, 2015; D. Wang, Dai, Ning, Dong, & Wu, 2017). Chronic exposure, in severe cases, can result in permanent disability. Throughout their work life, construction workers master habits which if uncorrected could translate into behaviors that novice workers or trainees could pick up over time (Laberge & Ledoux, 2011; Merlino, Rosecrance, Anton, & Cook, 2003; Schwatka, Butler, & Rosecrance, 2011).

Most often, awkward postures can be prevented by adequately educating or training construction workers to make them aware of (i) safe and unsafe postures for different tasks (Chaffin, Gallay, Woolley, & Kuciemba, 1986; Cheng, Migliaccio, Teizer, & Gatti, 2012; D. Wang et al., 2015), (ii) proper layout of workplaces (Chaffin et al., 1986; Lemasters et al., 1998; Ray & Teizer, 2012) and (iii) correct selection of tools or equipment (J. T. Albers et al., 1997; Buchholz, Paquet, Punnett, Lee, & Moir, 1996). In addition, safe work behaviors and practices have been promoted by safety and health organizations such as National Institute for Occupational Safety and Health (NIOSH) (J. Albers & Estill, 2007; Moore, Steiner, & Torma-Krajewski, 2011) and Occupational Safety and Health Administration (OSHA). These include training materials and programs to help construction workers recognize and avoid unsafe postures in their workplaces. Since these trainings are instruction-based, construction workers do not have many opportunities to try-out tasks and receive feedback based on direct observation of their work. Accordingly, providing postural training to construction workers while performing the actual task can be expensive and time-consuming; particularly due to access to ergonomic experts to monitor posture during construction work. In some cases, visual observation or inspection may not be accurate and reliable. Also, due to the cost of obtaining postural training, workers tend to resort to online instructional sources, where quality of instruction and transfer of training may be difficult to ascertain.

Advances in information technologies have resulted in the emergence of Cyber-Physical Systems (CPS), which offers a more effective approach to training workers by strategically adapting the instructional contents to the development or performance of the workers. There is evidence that CPS can provide a platform for situated and experiential learning which is transferable to practice (Abele et al., 2015; Törngren et al., 2015). Compared to the traditional approach to training workers, CPS strategically employs computational resources for real-time monitoring and understanding of the performance or behavior of learners and provides the training materials needed to achieve the learning objectives based on the positive and/or negative performance of the learners. By integrating virtual reality, wearable sensors and machine learning algorithms, ergonomic exposures of different body-parts of workers can be captured as workers practice work in a virtual environment, assessed and immediate feedback can be delivered based on the performance level until the worker has attained the required skill. Thus, this paper focuses on describing an on-going research aimed at employing CPS for developing the competencies of construction workers in performing work in safe postures.

2. Background

Over the years, safety and health organizations such as OSHA and NIOSH published guidelines for addressing general ergonomic and postural issues. For example, Moore et al. (2011) and J. Albers and Estill (2007) provided graphical guidelines for carrying out example construction tasks with alternative tools and equipment. In addition to other ergonomic risks, the manuals provide solutions for awkward postures such as reaching overhead or behind the head, twisting at the waist, bending the torso forward, backward, or to the side, squatting, kneeling and bending the wrist. Solutions to lifting loads from the ground surface can be accomplished by stooping or bending. Such postures, however, are not recommended for ergonomic reasons and in such cases, the methods shown in Fig. 1 are recommended. In-spite of these guidelines, several researchers (Van Eerd et al., 2016; X. Wang, Dong, Choi, & Dement, 2017) and the BLS (BLS, 2017) have reported increasing incidents of WMSDs. These guidelines are usually administered through online materials and instructor-led trainings (lecture or demonstration), relying on the belief that the learners will acquire safe postural skills by obtaining verbal or visual information. Learners have limited opportunities to practice the skill and obtain regular feedback based on inspection or direct observation of their work.

The advent of ubiquitous computational and control resources has provided opportunities for developing intelligent personalized learning environments for enhancing competencies of workers. Till date, most of the studies in the area of construction ergonomics has been focused on the identification and assessment of postures of construction workers (Chen, Qiu, & Ahn, 2017; Nath, Akhavian, & Behzadan, 2017; Yan et al., 2017). Little effort has been made in the area of enhancing cognitive and motor skills of construction workers to reduce work-related musculoskeletal injuries. A recent study by Sivanathan, Abdel-Wahab, Bosche, and Lim (2014) proposed a near CPS approach that employs sensing systems and gaming platform for tracking the movement of body-parts of construction workers and providing feedback based on their performance. The authors suggested that the feedback could be provided to the user via an audio alert. Since the workers are tracked while performing real construction activities, there are limited opportunities to digest the provided feedback and take corrective actions. This study addresses these limitations in the body of knowledge and complements the current practice by employing CPS for providing a personalized and flexible learning environment capable of engaging and adapting to learner's preferences while also obtaining feedback.

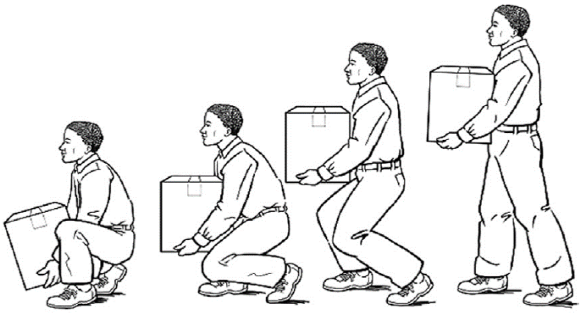


Figure 1: Ergonomic procedure of lifting load to reduce occurrence of back injury (J. Albers & Estill, 2007)

3. Cyber-Physical Postural Training System

The study aims to improve competencies of construction workers in performing work in safe postures through a CPS based postural training system. The developed CPS postural training system tightly integrates computational resources such as virtual reality, wearable sensors and machine learning, with the physical movements of construction workers (as shown the Fig. 2). Within a virtual environment, the developed system provides examples of how to perform real construction tasks in safe postures and practice exercises. The system employs wearable sensors for tracking the body-parts of learners as they implement practice exercises. The captured body rotation data are analyzed and used by the machine learning model. The machine learning model automatically learns the behavior or movement of the learner and provides instructional materials needed to achieve safe postures.

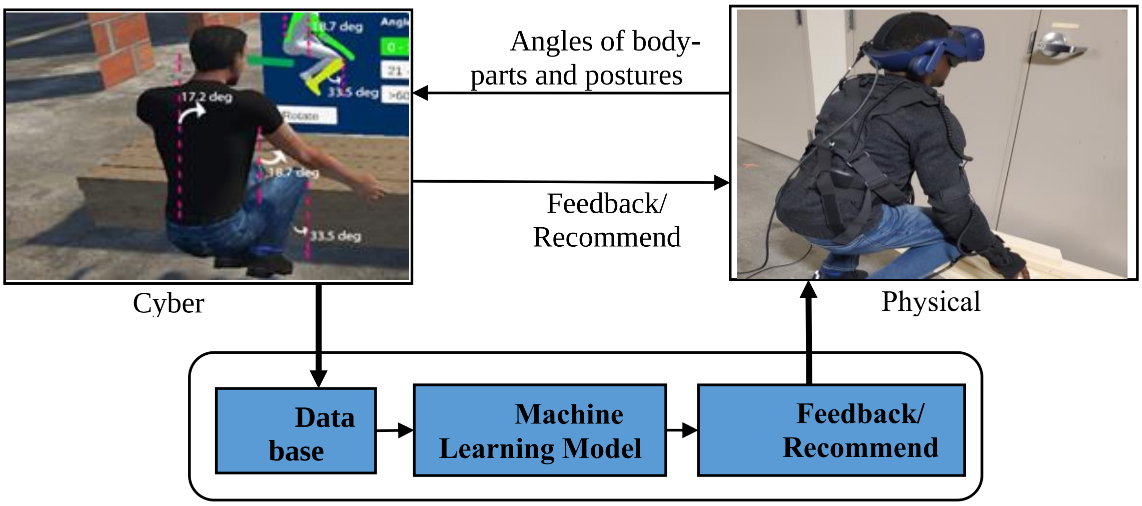


Figure 2: CPS for postural training

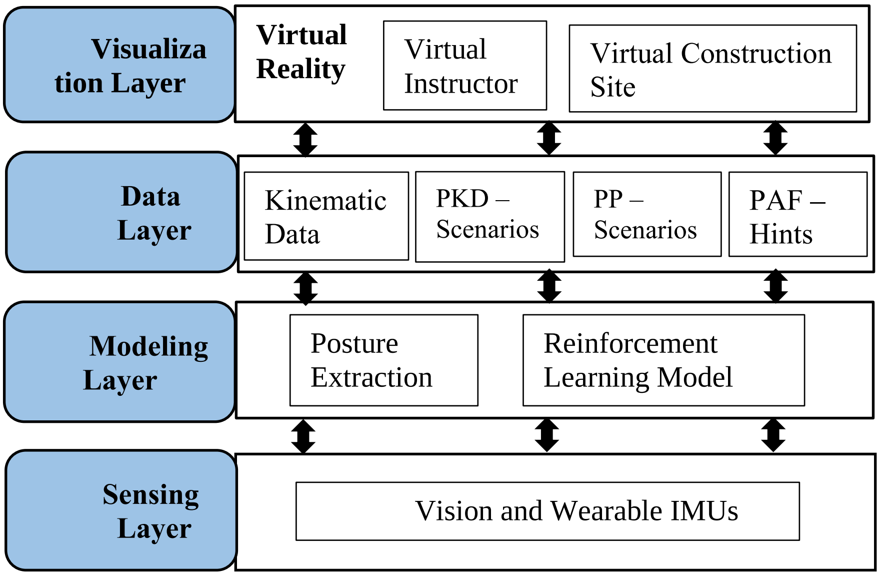
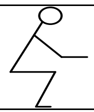
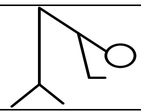


Figure 3: A framework for using CPS based postural training

Table 1. Example of safe and unsafe postures for 'Lifting wood' task

Safe Posture	Unsafe Posture
	

3.1 System Modules

The framework comprises of three modules: (1) Posture knowledge dissemination (PKD) to educate workers on what safe and unsafe postures are; (2) Posture practice (PP) to allow workers to try-out the knowledge acquired through real site activities, and (3) Posture assessment and feedback (PAF) to assess the performance of the worker and deliver instruction materials based on performance, as illustrated in Fig. 3. These modules are described as follows:

Posture Knowledge Dissemination: This module focuses on teaching and transferring postural knowledge. Prior to commencing training, it is important to provide learners with guidelines on how to assume safe and unsafe postures (Table 1), and types and levels of ergonomic risks associated with different body segments. This module provides construction workers with guidelines or illustrations on how to carry out construction work in safe postures. In this module, VR animations (Fig. 4) are used to illustrate the scenarios of safe postures for different construction tasks, allowing learners to clearly visualize how the construction tasks should be carried out on real site environments.

Posture Practice: This module consists of construction activities and tasks that will be executed by different construction trades. After learning the safe and unsafe postures from the PKD module, learners can select their trade and they will be provided a list of tasks to choose from. For each of the tasks selected, the learner will be provided with the materials and equipment required for executing the task. By replicating or practicing the construction tasks in the virtual environment, the learners are engaged in experiential learning. In comparison to other traditional methods, experiential learning significantly increases understanding and retention of learned materials, as learners are intrinsically motivated when they are actively engaged in the learning process (Cope & Watts, 2000; Reigeluth, 2013).

Posture Assessment and Feedback: This module will assess the workers' learning and determine if additional training is required for specific areas. This module extracts (1) the postures of the worker when training with the tasks from the posture practice module; (2) compares these with recommended or safe postures stored in the database; and (3) delivers the suitable instructional materials if additional training is required.

Figure 4: Learner observing safe postures to perform 'lift box' subtask

3.2 System Architecture

The system architecture for the CPS based postural training system consists of the following four layers: visualization layer, modeling layer, data layer and sensing layer, as shown in Fig. 3. These are described as follows:

Sensing layer: The sensing layer consists of vision and component-based sensing systems for tracking the movement of the body-parts when the learner is practicing work from the PP scenarios in the data layer. This CPS system uses a commercially available wearable sensor (PrioVR) consisting of 19 IMU sensors, a base-station and a hub. Each IMU consists of a 3-axis accelerometer, gyroscope, and magnetometer, which measures the acceleration and angular rotations of each of the segments of a learner's body. The hub collects data from each IMU and sends the data wirelessly to the base-station. The base-station communicates the received data to the computer over USB. This is shown in Fig. 5. The orientation data of each body-part are sent to a posture extraction algorithm in the data layer.

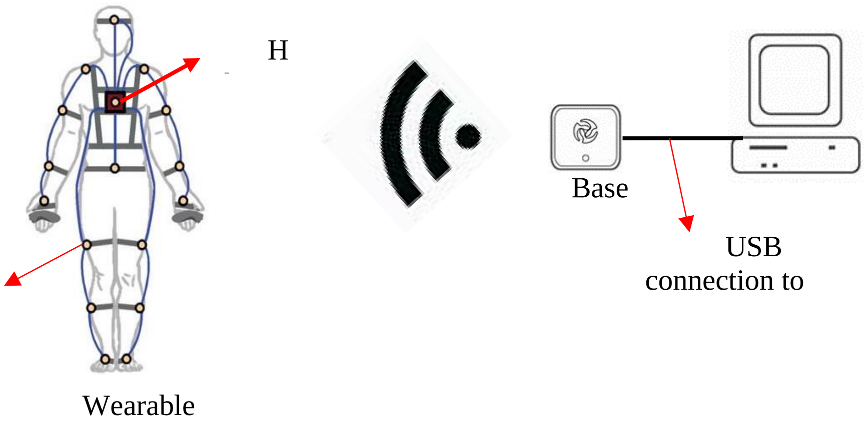


Figure 5: Wearable IMU – IMU, Base-station and Hub (Labs., 2007)

Modeling layer: The modeling layer implements the posture extraction and reinforcement learning models. The posture extraction algorithm uses the angles of the body-parts (obtained from the sensing layer) to generate postures. The reinforcement learning model was built based on the actor-critic learning algorithm (Peters & Schaal, 2008). The actor-critic reinforcement learning algorithm serves the following purposes: (i) diagnoses the knowledge and skill gaps of individual trainees in achieving safe postures on the virtual construction sites, and (ii) adapts the instructional contents and delivery methods according to the need of individual trainees. The diagnostic and adaptive capabilities are two essential qualities of a good teacher in maximizing learning (Hill, 2002; Iglesias, Martínez, Aler, & Fernández, 2009). The actor-critic reinforcement learning model defines the current state (of learning) according to the posture assumed and with respect to the learning scenarios administered. The policies (i.e., options for adapting the virtual instructor in the visualization layer) are a combination of learning aids/hints available in the PAF module. The actor-critic reinforcement learning model chooses a policy to adapt the virtual instructor when the postures are deemed unsafe ergonomically. If the trainees show posture improvements, the reinforcement learning model will not only continue with the policy but also reinforces or rewards the policy for that given state. However, if the posture continues to be unsafe, the reinforcement algorithm selects another policy and then negatively reinforces or punishes the policy for that given state. Actor-critic reinforcement learning model is highly suitable for developing the intelligence of the instructor because the posture assessment is automated, enabling the computation of reward and punishment for each policy for adapting the virtual instructor with respect to the state of learning.

Data layer: The data layer consists of the databases housing the body movement data (kinematic data), the risk classification, and the PP, PKD and PAF modules. The risk classification provides a way of quantifying risks associated with different body-parts through the rotation or angles of bent of the body-parts (Lowe, Weir, & Andrews, 2014). The higher the angle a body part bends, the more likely is the risk of awkward postures, hence, musculoskeletal disorders over time. To reduce observational errors, researchers have classified these angles into different risk levels (Chander & Cavatorta, 2017; David, Woods, Li, & Buckle, 2008; Lee & Han, 2013; Stanton, Hedge, Brookhuis, Salas, & Hendrick, 2004). This study employs the Postural Ergonomic Risk Assessment classification (Chander & Cavatorta, 2017) shown in Table 2, which is based on tasks involving repetitive subtasks and non-static postures.

Table 2: Risk Classification Chart

Body Part	No Risk	Low Risk	Medium Risk	High Risk
Trunk Flexion		0 – 20	21 – 60	>60
Trunk Lateral Flexion			0 – 10	>10
Shoulder Flexion		0 – 20	21 – 60	>60
Elbow Flexion		0 – 20	21 – 60	>60
Hip Flexion	0 – 30	31 – 60	61 – 90	>90

Visualization layer: The visualization layer includes the VR hardware, virtual construction site and the virtual instructor developed using the Unity3D gaming platform. The virtual construction site and the virtual instructor are delivered to the learner using the HTC Vive Pro device (VIVE, 2018). The virtual construction site consists of virtual construction site resources needed for demonstrating the scenarios in the PKD module and for implementing the tasks in the PP module. The virtual instructor delivers personalized information from the PKD, PP and PAF modules. The significance of the virtual instructor is to motivate the learner, reinforce the learning concepts, and provide guidance through the posture learning tasks. Asides the feedback from the PAF modules, the virtual instructor also educates the learner about the levels of risk associated with each IMU tagged body-parts. Different color codes are used to differentiate between the risks levels shown in Table 2. Each body-part can be colorized based on their angle of bent. On seeing the color of the body-part, the learner can take corrective actions. Figs. 6 and 7 show the learner performing construction tasks and the virtual instructor from a first person view.

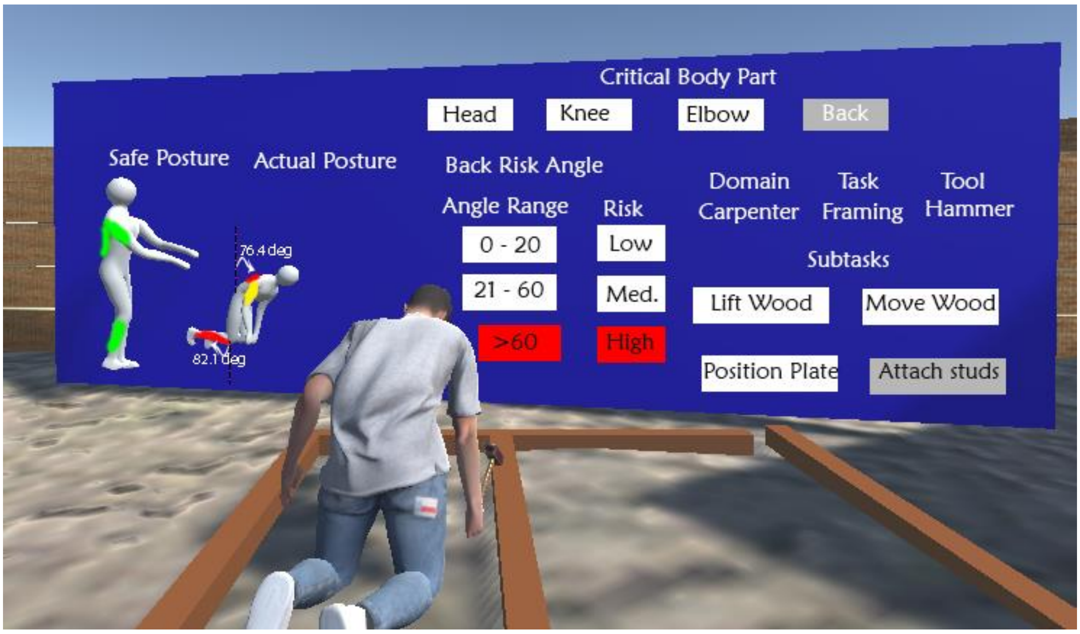


Figure 6: Learner performing framing task and the virtual instructor showing his posture

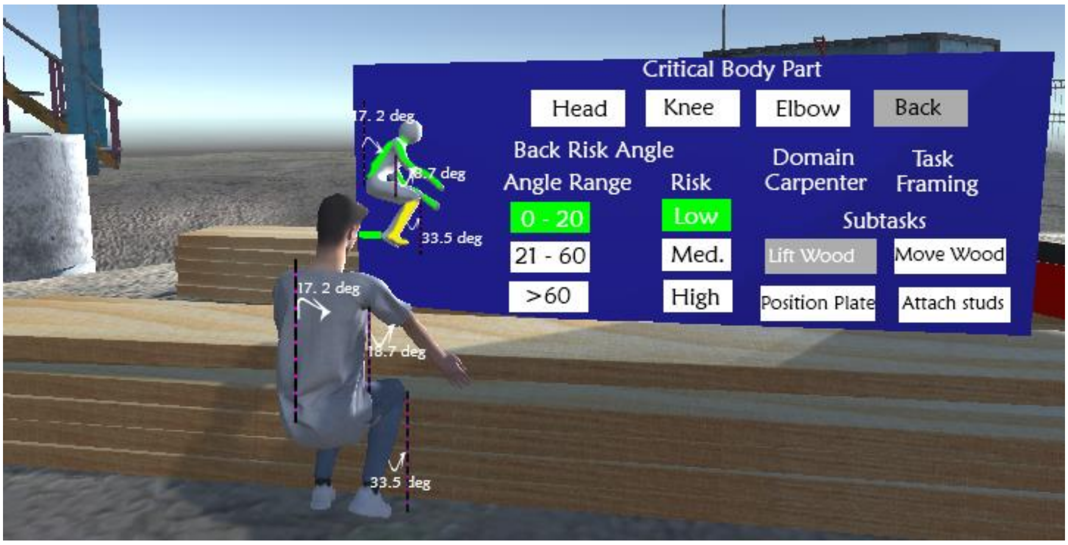


Figure 7: Learner performing 'lifting wood' subtask and virtual instructor showing his actual posture

4. Conclusions and Future Work

This paper has presented the development of a CPS based postural training system. An overview of the development of the preliminary prototype is presented. This includes the system architecture, modules and the virtual learning environment. With the aim of enhancing a tight integration between computational resources and physical movements of workers, the proposed CPS postural training tool offers advantages in educating inexperienced (novice or trainee workers) and the experienced workers in performing work in safe postures, thereby reducing the risk of musculoskeletal injuries. The developed system provides feedback via a virtual instructor in the VR environment in two ways: (1) by adapting instructional aids in the form of hints or illustrations on how to maintain safe postures and (2) by colorizing the body-part of the replica posture of the learner. Therefore, the performance of the learner can be evaluated and underperformances can be corrected. Future work on the preliminary prototype involves the following: conducting a usability analysis of the virtual instructor on different construction trades. The strength of the reinforcement learning model in adapting instructional aids lies in the amount of training data. More data will need to be collected for different trades to training the reinforcement model. Lastly, the developed prototype will be evaluated to examine its effectiveness for transferring the obtained knowledge and safe behavior to actual construction sites.

References

(BLS), B. o. L. S. (2018). Nonfatal Occupational Injuries and Illnesses in the Construction Industry. Retrieved from https://data.bls.gov/pdq/SurveyOutputServlet

Abele, E., Metternich, J., Tisch, M., Chryssolouris, G., Sihn, W., ElMaraghy, H., . . . Ranz, F. (2015). Learning factories for research, education, and training. Procedia CiRp, 32, 1-6.

Albers, J., & Estill, C. F. (2007). Simple solutions; ergonomics for construction workers.

Albers, J. T., Li, Y., Lemasters, G., Sprague, S., Stinson, R., & Bhattacharya, A. (1997). An ergonomic education and evaluation program for apprentice carpenters. American Journal of Industrial Medicine, 32(6), 641-647.

Bernard, B. P., & Putz-Anderson, V. (1997). Musculoskeletal disorders and workplace factors; a critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back.

BLS. (2017). Injuries, Illnesses, and Fatalities Retrieved from https://www.bls.gov/news.release/pdf/osh2.pdf

Buchholz, B., Paquet, V., Punnett, L., Lee, D., & Moir, S. (1996). PATH: a work sampling-based approach to ergonomic job analysis for construction and other non-repetitive work. Applied ergonomics, 27(3), 177-187.

Chaffin, D. B., Gallay, L. S., Woolley, C. B., & Kuciemba, S. R. (1986). An evaluation of the effect of a training program on worker lifting postures.

Chander, D. S., & Cavatorta, M. P. (2017). An observational method for postural ergonomic risk assessment (PERA). International journal of industrial ergonomics, 57, 32-41.

Chen, J., Qiu, J., & Ahn, C. (2017). Construction worker's awkward posture recognition through supervised motion tensor decomposition. Automation in Construction, 77, 67-81.

Cheng, T., Migliaccio, G. C., Teizer, J., & Gatti, U. C. (2012). Data fusion of real-time location sensing and physiological status monitoring for ergonomics analysis of construction workers. Journal of Computing in Civil Engineering, 27(3), 320-335.

Cope, J., & Watts, G. (2000). Learning by doing–an exploration of experience, critical incidents and reflection in entrepreneurial learning. International Journal of Entrepreneurial Behavior & Research, 6(3), 104-124.

David, G., Woods, V., Li, G., & Buckle, P. (2008). The development of the Quick Exposure Check (QEC) for assessing exposure to risk factors for work-related musculoskeletal disorders. Applied ergonomics, 39(1), 57-69.

Hill, P. W. (2002). What principals need to know about teaching and learning. The principal challenge: Leading and managing schools in an era of accountability, 43-75.

Iglesias, A., Martínez, P., Aler, R., & Fernández, F. (2009). Learning teaching strategies in an adaptive and intelligent educational system through reinforcement learning. Applied Intelligence, 31(1), 89-106.

Insurance, L. M. (2018). Liberty Mutual Workplace Safety Index. Retrieved from https://business.libertymutualgroup.com/business-insurance/Documents/Services/Workplace%20Safety%20Index.pdf

Laberge, M., & Ledoux, E. (2011). Occupational health and safety issues affecting young workers: A literature review. Work, 39(3), 215-232.

Labs., Y. (2007). PrioVR Dev Kit - User Manual. Retrieved from https://yostlabs.com/the_downloads/PrioVR/Documentation/Current/PrioVR%20User's%20Manual.pdf

Lee, T.-H., & Han, C.-S. (2013). Analysis of working postures at a construction site using the OWAS method. International Journal of Occupational Safety and Ergonomics, 19(2), 245-250.

Lemasters, G., Atterbury, M., Booth-Jones, A., Bhattacharya, A., Ollila-Glenn, N., Forrester, C., & Forst, L. (1998). Prevalence of work related musculoskeletal disorders in active union carpenters. Occupational and environmental medicine, 55(6), 421-427.

Lowe, B. D., Weir, P., & Andrews, D. (2014). Observation-based posture assessment: review of current practice and recommendations for improvement.

Merlino, L. A., Rosecrance, J. C., Anton, D., & Cook, T. M. (2003). Symptoms of musculoskeletal disorders among apprentice construction workers. Applied occupational and environmental hygiene, 18(1), 57-64.

Moore, S. M., Steiner, L. J., & Torma-Krajewski, J. (2011). Practical demonstrations of ergonomic principles.

Nath, N. D., Akhavian, R., & Behzadan, A. H. (2017). Ergonomic analysis of construction worker's body postures using wearable mobile sensors. Applied ergonomics, 62, 107-117.

Peters, J., & Schaal, S. (2008). Natural actor-critic. Neurocomputing, 71(7-9), 1180-1190.

Ray, S. J., & Teizer, J. (2012). Real-time construction worker posture analysis for ergonomics training. Advanced Engineering Informatics, 26(2), 439-455.

Reigeluth, C. M. (2013). Instructional-design theories and models: A new paradigm of instructional theory (Vol. 2): Routledge.

Salas, E. A., Vi, P., Reider, V. L., & Moore, A. E. (2016). Factors affecting the risk of developing lower back musculoskeletal disorders (msds) in experienced and inexperienced rodworkers. Applied ergonomics, 52, 62-68.

Schwatka, N. V., Butler, L. M., & Rosecrance, J. R. (2011). An aging workforce and injury in the construction industry. Epidemiologic reviews, 34(1), 156-167.

Sivanathan, A., Abdel-Wahab, M., Bosche, F., & Lim, T. (2014). Towards a cyber-physical gaming system for training in the construction and engineering industry. Paper presented at the ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.

Stanton, N. A., Hedge, A., Brookhuis, K., Salas, E., & Hendrick, H. W. (2004). Handbook of human factors and ergonomics methods: CRC press.

Talk, S. (2015). Ergonomic Principals - Awkward Posture. Retrieved from http://www.colby.edu/humanresources/wp-content/uploads/sites/170/2015/05/Ergo-Safety-03-Talk.pdf

Törngren, M., Bensalem, S., McDermid, J., Passerone, R., Sangiovanni-Vincentelli, A., & Schätz, B. (2015). Education and training challenges in the era of Cyber-Physical Systems: beyond traditional engineering. Paper presented at the Proceedings of the WESE'15: Workshop on Embedded and Cyber-Physical Systems Education.

Van Eerd, D., Munhall, C., Irvin, E., Rempel, D., Brewer, S., Van Der Beek, A., . . . Pinion, C. (2016). Effectiveness of workplace interventions in the prevention of upper extremity musculoskeletal disorders and symptoms: an update of the evidence. Occup Environ Med, 73(1), 62-70.

VIVE. (2018). HTC Vive. Retrieved from https://www.vive.com/us/product/vive-virtual-reality-system/

Wang, D., Dai, F., & Ning, X. (2015). Risk assessment of work-related musculoskeletal disorders in construction: State-of-the-art review. Journal of Construction Engineering and management, 141(6), 04015008.

Wang, D., Dai, F., Ning, X., Dong, R. G., & Wu, J. Z. (2017). Assessing work-related risk factors on low back disorders among roofing workers. Journal of Construction Engineering and management, 143(7), 04017026.

Wang, X., Dong, X. S., Choi, S. D., & Dement, J. (2017). Work-related musculoskeletal disorders among construction workers in the United States from 1992 to 2014. Occup Environ Med, 74(5), 374-380.

Yan, X., Li, H., Wang, C., Seo, J., Zhang, H., & Wang, H. (2017). Development of ergonomic posture recognition technique based on 2D ordinary camera for construction hazard prevention through view-invariant features in 2D skeleton motion. Advanced Engineering Informatics, 34, 152-163.

Designing blockchain applications for construction project management

George Blumberg
School of the Built Environment
Oxford Brookes University Gipsy Lane, Oxford, ox30bp
email: gblumberg@brookes.ac.uk

Abstract

This paper describes the results of a study into the application of blockchain technology to construction and engineering (C&E) projects. Through design and simulation, the specification for an open source software framework and the architecture is provided that can support project governance through the use of a blockchain and extended modules. This work demonstrates that the technology is at a suitable stage of development to allow implementation to start for basic processes and that rapid progress of useful modules are expected to follow shortly.

Keywords: Blockchains, project management in construction

1. Introduction to the study

Many have written (Swan, 2015) and spoken[1] about blockchains as a revolutionary platform technology with numerous applications across industry, government and civil society (Glaser, 2017). The application of the technology to commercial activities promises to provide benefits far beyond its original purpose (Hultgren and Pajala, 2018; Turk and Klinc, 2017), including for construction and engineering (C&E) assembly and administration (Penzes 2018; Hultgren and Pajala, 2018) that could lead to automation. For example, secure payments made using smart contracts embedded in the blockchain software and triggered when all contractual conditions are met. These services can be provided independently of any central authority (López-Pintado, et. al., 2018), a feature particularly useful when trading partners are not entirely trusting of each other and when delays in payment introduces additional financial risk (Tapscott and Tapscott, 2017; Carroll and Bellotti, 2015). Indeed, further automation of a range of assembly and administration processes could provide broad benefits across an industry that is known for low productivity and profits (Barbosa et al., 2017). Additional features of the technology can provide similar functionality as Enterprise Resource Management (ERM) system, providing a low-cost alternative to these solutions.

Additionally, a good design of a blockchain system (Li, et. al., 2017) would help address heightened concerns about the safety of buildings (Brokenshire, 2018) as project governance and continuity have been identified as areas that need improvement. Indeed, any effort to further introduce digital technology would help achieve government industrial strategy for the sector (Cable et al., 2013). Solutions abound in other fields, such as an online voting system (Marella, et.al., 2017), systems for protecting personal data (Zyskind et al., 2015) and as a basis for interconnected and distributed services fundamental for the Internet of Things (Christidis and Devetsikiotis, 2016).

But despite these imperatives to adopt this new technology, there are several factors that are impeding implementation, the main one being the lack of fully featured commercial applications. There are an abundance of prototype systems, but most companies do not progress their projects beyond the pilot stage (Lacity, 2018), a fact that indicates some reluctance to adopt the new technology. Other factors are slowing widespread adoption. For example, many are sceptical about prospects of rapid-

[1] The Ted Talk by Bettina Warburg is a good introduction to the potential of the technology: www.ted.com/talks/bettina_warburg_how_the_blockchain_will_radically_transform_the_economy

scale destructive innovation and the hype (Pardolesi and Davola, 2019) associated with the technology, and with cryptography (that uses the same technology) which is associated with wild speculation (Fry and Cheah, 2016), quick fortunes won and lost (Decker and Wattenhofer, 2014) and illegal activities (De, 2019; Stroukal et al., 2016; Barone and Masciandaro, 2019; Buchanan et al., 2018). There is also the realisation that although adoption might help the industry as a whole, the direct benefits to individual companies may be illusive and investment therefore hard to justify. Evidence also shows that although many UK construction companies are favourable towards change (Waterhouse et al., 2017), such as by seeking out new technology (Waterhouse et al., 2019), engaging in collaborative relations with suppliers and clients (Akintoye and Main, 2007) and adopting Modern Methods of Construction (MMC) (Raynsford et al., 2016). The industry is still characterised as having low levels of trust (Cerić, 2015), for being adverse to change and slow to adopt innovation and for low profitability (Green, 2016; Davis et al., 2015). Construction is also known as a locus of crime (Warne, 2016) and for being associated with illegal and immoral business practices (Pontell and Geis, 2007). Despite these aspects, there is great enthusiasm for the promotion of blockchain technology and the field is progressing rapidly. Optimistically, there are few industries less likely to benefit from this innovation than construction the UK which is both driven-to and receptive-for change (Egan, 1998; Latham, 1994). This paper will explain how this technology can be introduced.

2. Aims and objectives of the technical paper and summary of the logic followed

The overall long-term aim of this research programme is to identify design, test, evaluate and plan for adoption of emerging technology to improve the management of C&E projects. The specific objectives of this paper are to:

(i) Define, through business process modelling, a suitable blockchain platform for use on C&E projects.
(ii) Propose a system architecture and configuration for a blockchain solution that is able to support C&E projects.
(iii) Discuss the relative merits on the use of blockchain technology for C&E projects based on criteria established through pilot studies.

3. Methods used in this study

This section describes the approach taken to accomplish the research objectives and make progress towards achieving the long-term aim. One of the main tasks is to define a blockchain application that is able to support C&E projects. There are several aspects of this. Firstly, at the time of writing, there are no full-featured, commercial systems on the market. Open source modular systems require a higher level of effort but with the added advantage that it forces a modular approach to problem-solving and creates the opportunity for creative innovation. The introduction of blockchains technology to construction management requires modelling of the business processes (García-Bañuelos et. al., 2017) in a similar manner to an ERM application. Thus business process mapping is a common approach to automation with a shift to customer interaction using mobile devices and as part of a distributed, client-side application (Viriyasitavat et al., 2018). The so-called artifact (sic) centric business process model (Nigam and Caswell, 2003) is a common method for modelling business processes. These are well documented in business literature (see Waller, 2003). Seebacher and Maleshkova (2018) helped to understand the graphical and model-driven tools for the blockchain business network. Grapical methods can help. For example, Damelio (2016) described the swim-lane chart that was helpful in modelling the individual chain of transactions that define ordering protocols of the process.

These and other aspects of the design and configuration for C&E projects requires a design for the system architecture that is optimised for the business process, including aspects such as the consensus and ordering protocols. To aid in defining these, Wang et al. (2018b) provides an understanding of how to configure a functioning consensus mechanism across networks and Cachin and Vukolić (2017) a practical guide to ensuring that the individual transactions are ordered correctly so that the trading record is accurate and reliable. This helps in the forensic analysis of a project and can help to determine if any accounting fraud or double payments occurred.

The approach taken to evaluate the relative merits on the use of blockchain technology for C&E projects based on criteria established through pilot studies. This is a long-term task as it also requires that some form of adoption plan be promoted. This plan will required a detailed evaluation of the current methods and a solid argument as to how blockchain technology can be used to either enhance or replace the existing systems. Separate evaluation is required to determine if the proposed system is robust enough to stand up to use in demanding industrial and commercial settings. A survey of the numerous pilot projects that have been reported helps with this evaluation as well as in-house testing using an open source system that was installed and configured as a simulated process.

4. Description of the blockchain technology suitable for project management

This section contains a description of a blockchain solution that would be suitable for use on C&E assembly and administrative processes[2]. This stage is essential in the study as it provides a working model to apply the new technology. As blockchains are considered a disruptive technology with applications and impact that have the potential to dramatically change normal working practice. Although this study focuses on a specific case where the blockchains are used to log transactions associated with the installation of series of offsite manufactured building components. Other process, such as the management of staff on site, or warranty conditions for installed M&E systems, might benefit from an application of the technology. Current practice for the management of component installation range from project to project and might include the use of standard paper or spreadsheet-based ledgers to record some (but not all) of the transactions. Additionally, commercial project management software (e.g. *Asta Powerproject* and *Microsoft Project*) have the capability record orders, deliveries, installations, inspects and so forth that can be used to update Gantt charts and to produce reports for Cost Value Reconciliations (CVR) and other methods to monitor and measure expenditures against budgets on construction projects.. But these systems lack certain features that blockchains could provide, most notably as a method to automate processes. These are:

(i) Transactions between members of a trading network are recorded and stored in an immutable ledger for later use or to trigger (with smart contracts) for actions such as communications or automatic payments.

(ii) The system, through extended modules can support realistic trading activities by providing services of the sort normally found in ERM applications[3].

(iii) That security and privacy are maintained to a level that is appropriate for a commercial operation.

In order to illustrate ow these features function and help, consider the diagram in Figure 1 which shows five (5) separate transactions of an *asset* (i.e. *a building component*) between members of a trading network (*Nodes* in this example).

[2] The ZeroToBlockchain practical and video series by Gill (2018) provides a template for a blockchain system that is suitable for use in project management.

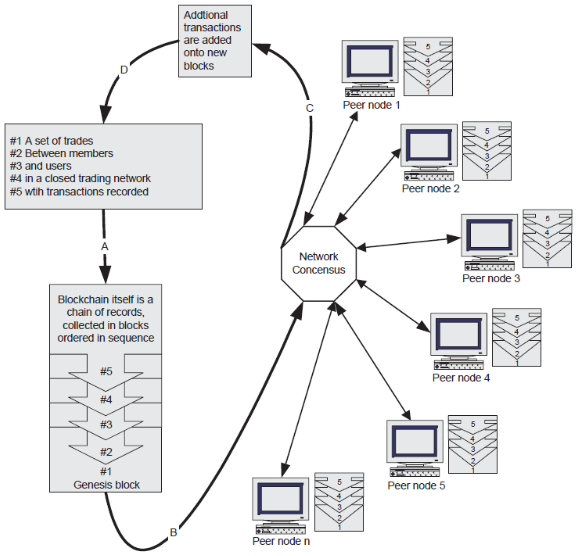


Figure 1: This diagram shows a simplified schematic of how the core blockchain functions. It is a flow chart describing how transactions are recorded on a blockchain. Arrows show the direction of the records of transactions as they are written on the blockchain, passing first through the central network consensus algorithm and on to the Peer nodes.

The arrow labelled **A** starts the process where transactions are sent to the *Peer nodes* for confirmation via a network consensus (arrow **B**) protocol, which is represented by the central octagonal box. The arrow labelled **C** shows how the process repeating cyclically with additional transactions recorded (arrow **D**). What makes the blockchain immutable is that each block of transactions is encrypted with a hash and the key is then stored in the block that follows. A cryptographic hash acts a one-way function that, once the blocks have been strung together, they can only be read by undoing them in sequence (Finck, 2018). The use of a cryptographic algorithm ensures a level of security (Szabo, 1997) that protects against hostile attempts to alter the record or obtain confidential data. If there is any attempt to alter or add data, then it will be impossible to reconstruct the data as it was before.

At the core of this system is a consensus and ordering algorithm, which is critical for the function of this business-oriented blockchain (Swanson, 2015). This ensures that partners engaged in a trade have a contract in place and that their right to trade is accepted and authorised by the other members of the network (even if they don't get to see the details of the trade) and that transactions are ordered sequentially. The consensus process, if properly configured, makes it difficult for fake, falsify or enter the same transaction. Although double-entry costs can sometimes occur by accident, fake ledger entries are hallmarks of organised crime[4]. For C&E projects, as in other commercial settings, a commonly used protocol is *Byzantine fault tolerance* (Lamport et al., 1982). This approach to consensus and ordering is based on the acceptance that one or more of the nodes might be out of service or, for some reason, contain false information (Cachin and Vukolić, 2017).

5. Digital ledger technology and the extended blockchain system

This section contains a description of the architecture of an extended blockchain system that to make it suitable for C&E projects. These additional elements make up a complete system (Xu et al., 2019; Wang et al., 2018a) that is collectively referred to as Digital Ledger Technology (DLT). Fortunately, a framework is available that can provide the features required. The Hyperledger Fabric (HLF) framework[5] is an implementation based on a series of projects (Androulaki et al., 2018) and

[4] See Beare (2007, p43) for a legal perspective of the issues around double-billing

[5] Hyperledger Fabric v1.4 can be downloaded at github.com/hyperledger/fabric.

published as part of the Hyperledger consortium (Hyperledger, 2017). This is an open software development community[6] managed by the not-for-profit Linux Foundation®. The requirements of the proposed system dictate an architecture of the HLF that is illustrated in Figure 2. This includes the following elements: (i) network designers that set up the initial configuration of endorsement and consensus algorithms, (ii) system administrators that manage deployment, membership management, smart contracts and system maintenance, (iii) a world state (i.e. a database) that contains the current status of the assets, (iv) a peer network, containing the distributed ledger and applications and (v) events management and notification system.

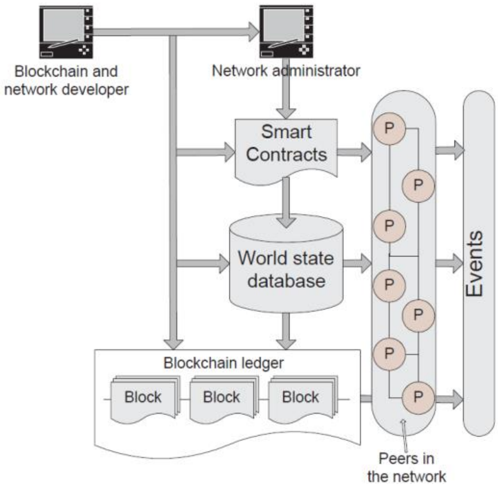


Figure 2 contains the basic system architecture of the DLT that includes the administrator and developer, smart contracts, world state database, peers and events based upon the HLF implementation. Peers are identified by the symbol 'P'.

The network developer and administrator, shown near the top of Figure 2 share a range of responsibilities in the deployment and administration of the DLT. Operating through a software development kit (SDK), they build and maintain the network, members and events. In HLF the membership manager can create, stop, change the configuration or, if required, delete the peers (Dunphy and Petitcolas, 2018). Members can extend beyond the Peers. For example, the shipper, responsible for delivering components on site would be able to query the DLT (or be prompted by a message) for the expected time of delivery, then once one site, register the delivery with a countersign by the site foreman. This could all be done using RFID tags, digital signatures, drop down menus and tick-boxes on module devices.

What is not shown in Figure 2 are some of the finer features of the DLT, notably how the consensus algorithm works and the way that smart contracts are embedded into the core blockchain or how the interface uses pull-down menus, check boxes and other forms of browser-based information exchange to interact with the DLT. Significantly, the system had the capability to manage separate sets of ledgers (i.e. blockchains) for each channel. Multiple channels are essential in that they that allow trading partners to maintain privacy. This protects confidential commercial data, but still allows mission-critical information such as the delivery date, warranty details and maintenance instructions, to be available for a wider audience. Membership profiles are controlled by the network administrator (López-Pintado et al., 2018). But this arrangement has the disadvantage in that some of the channel blockchains are saved on only two or three nodes. This could be a problem if any one of these nodes were to become unavailable, and could lead to a slowing down or bringing to a halt the project. One way around this is to host the DLT on a cloud computing system provided by a company that with mission-critical reliability and security.

[6] See Anon. (2016) and Söderberg (2015) for a general overview of the open source movement and Glaser (2017) for a discussion related to open source blockchains.

6. Business processes management in construction using blockchains

It is useful to consider added feature DLT when used in a commercial setting. Although primarily designed to record transactions, an added benefit of DLT is their ability to emulate an ERM. If configured properly, they can be used to monitor, record and control business and technical information, record critical dates and receive digital signatures for approval and implements complex contracts. DLT can (with some effort), be made to interact with relational databases, mobile sensors, hand-held devices, analytical machines, ERM systems and Building Information Models (BIM) (Swan, 2015). However, this integration requires that the business process is carefully mapped (Auberger and Kloppmann, 2017). This is done with the artifact (sic) centric business process model (Damelio, 2016; Nigam and Caswell), where multi-thread and multi-component processes are organised around service provision to online clients (Waller, 2003).

Design process to set up a distributed ledger system

Figure 3 demonstrates the flow chart associated with an example of a building component installation cycle. Modelling requires an iterative approach with modelling and optimisation to achieve an accurate representation (Garcia-Bañuelos et al., 2017) that is ultimately used to configure the DLT (Seebacher and Maleshkova, 2018). This example process starts when the Design Coordinator (DC) submits a set of drawings to a communal repository, accessible only to those who require it. This submission triggers the Network Administrator (NA) to *Deploy* the DLT so that the PM can *Invoke* the first transaction. This is shown in the left of Figure 3. In this flow chart, the process proceeds with the delivery of the component on site, then installation, inspection and finally, certification. The cycle then returns to the top with the delivery of another component.

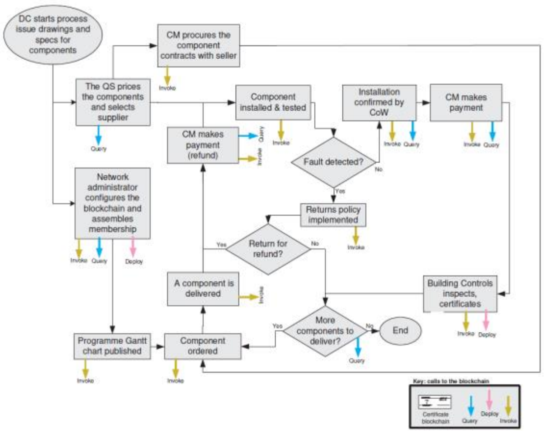


Figure 3 is a flow chart that shows the process of installation of the component that was made off-site. Those involved in this are the project manager (PM), Building Control (BC), Contract Administrator (CA), component supplier (SU), installer (IN) and Clerk of Works (CoW), who works for the client. Users are restricted to their access to the DLT to Deploy, Invoke or Query. These are represented by arrows extending from the task boxes.

Two sets of chaincode (smart contracts) are *Deployed* in separate blockchains in this example. The first one mirrors the paper contract between the component Supplier and the Client. The other one is *Deployed* by the Building Control (BC) regulator who uses a blockchain to save certificates required to authorise the safe occupancy of the building. The BC is responsible for confirming that each installation is done according to the building code and registers this by confirmation by invoking the blockchain to create a digital certificate that serves as an official mark of compliance. Certificates written to the blockchain and can be read by anyone with access privilege. Some members of the network receive signals (in the form of a text message, email or notification) when an event is triggered to indicate that action is required. For example, the Installer would receive notification on his mobile device when a component is ready for fixing into place. The exact location (floor and room number) for each component would also be conveyed in the DLT, so that, for example, the crane operator, plumber and other technicians can play their roles.

The extended-function DLT is created using Hyperledger Composer and as the framework is extensible, modules and templates are used to provide the range of services required.

7. Conclusions, discussion and recommendations

These conclusions reflect on the research objective set out in the introduction. Further discussion is included on a range of questions raised as a result of the research and recommendations are made on how to further evaluate the technology and plan for its adoption. One of the key objectives of the study was achieved by reviewing currently available DLT systems. Based on this, it was determined that Hyperleger Fabric and Hyperledger Composer is a suitable platform. The system architecture is proposed that allows the DLT to be used in a commercial setting using a mixture of fixed computers to serve as nodes and mobile devices to enter data and receive communications. A system architecture is presented in this paper that is driven by the design of the business process and configuration for a blockchain solution that is able to support C&E projects.

The adoption of Modern Methods of Construction (MMC) involves off-site component manufacturing of bathroom and kitchen pods, door sets, and structural insulated panels (SIPS), precast concrete foundation, ceiling and floor slabs. This is further proof that this is a controlled industrial process (Pan and Goodier, 2011; Slaughter, 1998) and therefore suitable for automation using an enterprise IT system. Furthermore, HLF requires no licence fee payment.

Automation of the construction process is mostly about the coordination of components made off-site using MMC and Lean manufacturing. So far, there has been little interest shown in large-scale integration of processes in construction. This may be because of the high costs (and significant risk) of installing an IT system. One of the big advantages of DLT is that it can be installed piecemeal, with processes added on as they are needed. The rapid advances in finding solutions to sometimes obscure problems that open software frameworks offers, makes DLT ideal for this particular industry. This finding is based on the general requirements of C&E projects of the sort of modelled in this study that extends the recording, communication and data management as an improvement of the systems created for cryptocurrency trading.

One aspect of construction projects that cannot be neglected is that the trading environment, with multiple components, suppliers and subcontractors, is complex and risky. Traders would benefit from a shared database and permanent record that contains information from which members can read from and write to, depending on their requirements (Greenspan, 2015). These might be needed in the case of disputes or conflicts between trading partners, or in the event of a defective component, accidental double invoicing, or if there is a high likelihood of graft, fraud or untraceable expenses. It is unfortunate that in many C&E projects there exists a fundamental absence of trust amongst partners.

Prospects for adoption of the technology are promising and this research provides a basis for future work. Functions such as controlling access to a site, managing supply chains, recording deliveries and material handling is possible with current DLT and a number of pilot and proof-of-concept studies (Korpela et al., 2017), including a joint venture between IBM and Maersk (Hackius and Petersen, 2017), provide the promise of technically feasibility[7].

References

Akintoye, A. and Main, J. (2007). Collaborative relationships in construction: the uk contractors' perception. Engineering, Construction and Architectural Management, 14(6):597–617.

Alarcón, L. (1997). Lean construction. CRC Press.

[7] It has been reported that wider adoption of the technology by partners have been slow (Allison, 2018).

Allison, I. (2018). ibm and Maersk struggle to sign partners to shipping blockchain. Coindesk online publication, https://www.coindesk.com/a-multibillion-dollar-cryptocurrency-based-on-lies-us-arrests-alleged-onecoin-leader. Accessed: 2 April 2019.

Androulaki, E., Barger, A., Bortnikov, V., Cachin, C., Christidis, K., De Caro, A., Enyeart, D., Ferris, C., Laventman, G., Manevich, Y., Muralidharan, S., Murthy, C., Nguyen, B., Sethi, M., Singh, G., Smith, K., Sorniotti, A., Stathakopoulou, C., Vukolić, M., Cocco, S. W., and Yellick, J. (2018). Hyperledger fabric: A distributed operating system for permissioned blockchains. In Proceedings of the Thirteenth EuroSys Conference, EuroSys '18, pages 30:1– 30:15, New York, NY, USA. ACM.

Anon. (2016). Linux and aws, cloud chronicles, how open-source software and cloud computing have set up the it industry for a once-in-a-generation battle. The Economist Magazine.

Auberger, L. and Kloppmann, M. (2017). Combine business process management and blockchain. 15. Online tutorial, retrieved 1 Mar 2019 from: developer.ibm.com/tutorials/ mw-1705-auberger-bluemix/.

Barone, R. and Masciandaro, D. (2019). Cryptocurrency or usury? crime and alternative money laundering techniques. European Journal of Law and Economics, pages 1–22.

Beare, M. E. (2007). The devil made me do it: business partners in crime. Jnl of Financial Crime, 14(1):34–48.

Brokenshire, J. (2018). Building a safer future: An implementation plan. Presented to parliament, Secretary of State for Housing, Communities and Local Government.

Buchanan, W., Dyson, S., and Bell, L. (2018). The challenges of investigating cryptocurrencies and blockchain related crime. The JBBA, 1(2).

Cachin, C. and Vukoli´c, M. (2017). Blockchain consensus protocols in the wild. arXiv preprint arXiv:1707.01873.

Carroll, J. M. and Bellotti, V. (2015). Creating value together: The emerging design space of peer-to-peer currency and exchange. In Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing, CSCW '15, pages 1500–1510, New York, NY, USA. ACM.

Cerić, A. (2015). Trust in construction projects. Routledge (Taylor & Frances Group).

Damelio, R. (2016). The basics of process mapping. Productivity Press.

Davis, R., Wilen, A., Crane, T., Bryer, L., Ward, D., Pottier, F., Cavin, L., Blofeld, S., and Blackwell, M. (2015). Uk industry performance report-2015. Construction Industry Key Performance Indicators2015.

De, N. (2019). A multibillion-dollar cryptocurrency based on lies: Us arrests alleged onecoin leader. Coindesk online publication, https://www.coindesk.com/a-multibillion-dollar-cryptocurrency-based-on-lies-us-arrests-alleged-onecoin-leader. Accessed: 2 April 2019.

Decker, C., & Wattenhofer, R. (2014, September). Bitcoin transaction malleability and MtGox. In European Symposium on Research in Computer Security (pp. 313-326). Springer International Publishing

del Castillo, M. (2019). Blockchain 50: Billion dollar babies. Forbes Magazine, Crypto & Blockchain, published online. Retrived April 20, 2019 at www.forbes.com/ sites/michaeldelcastillo/2019/04/16/blockchain-50-billion-dollar-babies/ #2e0d0c1657cc.

Dunphy, P. and Petitcolas, F. A. (2018). A first look at identity management schemes on the blockchain.

IEEE Security & Privacy, 16(4):20–29.

Egan, J. (1998). Rethinking Construction (the Egan Report). Technical report, Department of the Environment, Transport and the Regions, HMSO.

Enshassi, A., Mohamed, S., Mustafa, Z. A., and Mayer, P. E. (2007). Factors affecting labour productivity in building projects in the gaza strip. Journal of civil engineering and management, 13(4):245–254.

Finck, M. (2018). Blockchains and data protection in the european union. Eur. Data Prot. L. Rev., 4:17.

Fry, J. and Cheah, E.-T. (2016). Negative bubbles and shocks in cryptocurrency markets. International Review of Financial Analysis, 47:343–352.

García-Bañuelos, L., Ponomarev, A., Dumas, M., and Weber, I. (2017). Optimized execution of business processes on blockchain. In Carmona, J., Engels, G., and Kumar, A., editors, Business Process Management, pages 130–146, Cham. Springer International Publishing.

Gill, R. (2018). Zero to blockchain, video tutorial series and associated learning material. The complete course including code and videos are available for download. Retreived 1 Feb 2019, www.redbooks.ibm.com/Redbooks.nsf/RedbookAbstracts/crse0401.html.

Glaser, F. (2017). Pervasive decentralisation of digital infrastructures: a framework for blockchain enabled system and use case analysis.

Green, B. (2016). Productivity in construction: creating a framework for the industry to thrive.

Greenspan, G. (2015). Avoiding the pointless blockchain project. Chartered Institute of Building, Bracknell, available online (accessed March 2019. MultiChain, blog.

Hackius, N. and Petersen, M. (2017). Blockchain in logistics and supply chain: trick or treat? In Proceedings of the Hamburg International Conference of Logistics (HICL), pages 3–18. epubli.

Hultgren, M. and Pajala, F. (2018). Blockchain technology in construction industry: Transparency and traceability in supply chain. Unpublished Masters dissertation, Royal Swedish Institute of Technology.

Hyperledger (2017). Hyperledger announces production-ready Hyperledger Fabric 1.0.

Korpela, K., Hallikas, J., and Dahlberg, T. (2017). Digital supply chain transformation toward blockchain integration. In proceedings of the 50th Hawaii international conference on system sciences.

Koskela, L. (1992). Application of the new production philosophy to construction, volume 72. Stanford university Stanford.

Lacity, M. C. (2018). Addressing key challenges to making enterprise blockchain applications a reality. MIS Quarterly Executive, 17(3):201–222.

Lamport, L., Shostak, R., and Pease, M. (1982). The byzantine generals problem. ACM Transactions on Programming Languages and Systems (TOPLAS), 4(3):382–401.

Latham, S. M. (1994). Constructing the team.joint review of procurement and contractual arrangements in the united kingdom construction industry. final report. Technical report, HMSO.

Li, J., Greenwood, D., and Kassem, M. (2018). Blockchain in the built environment: analysing current applications and developing an emergent framework. Diamond Congress Ltd.

Li, X., Jiang, P., Chen, T., Luo, X., and Wen, Q. (2017). A survey on the security of blockchain systems. Future Generation Computer Systems.

López-Pintado, O., Dumas, M., García-Bañuelos, L., & Weber, I. (2018). Dynamic Role Binding in Blockchain-Based Collaborative Business Processes. arXiv preprint arXiv:1812.02909.

Marella, P. B., Mohler, J., Milojkovic, M., (2017). Broncovotes: Secure voting system using Ethereum's blockchain. Idaho Conference on Undergraduate Research

Mason, J. (2017). Intelligent contracts and the construction industry. Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 9(3).

Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system. Published online at: https://bitcoin.org/bitcoin.pdf.

Nigam, A. and Caswell, N. S. (2003). Business artifacts: An approach to operational specification. IBM Systems Journal, 42(3):428–445.

Pan, W. and Goodier, C. (2011). House-building business models and off-site construction take-up. Journal of Architectural Engineering, 18(2):84–93.

Pardolesi, R. and Davola, A. (2019). What is wrong in the debate about smart contracts. Available at SSRN.

Pasquire, C. L. and Connolly, G. E. (2002). Leaner construction through off-site manufacturing. Proceedings IGLC, Gramado, Brazil, pages 263–266.

Penzes, B. (2018). Blockchain technology in the construction industry. Technical report, Institution of Civil Engineers. Online publication. Downloaded on 15 Apr 2019 from www.ice.org.uk/ICEDevelopmentWebPortal/media/Documents/News/Blog/Blockchain-technology-in-Construction-2018-12-17.pdf.

Pontell, H. N. and Geis, G. (2007). International handbook of white-collar and corporate crime. Springer.

Raynsford, N., Briginshaw, J., Burke, A., Cook, R., Curtis-Thomas, C., Davies, H., Day, A., Denness, R., Finn, M., Fudge, C., Hardy, R., Harral, R., Hill, R., Jefferson, N., MacEachrane, R., CBE, R. N., Oreszczyn, T., Pearce, G., Quinton, M., Saunders, H., Turner, S., von Bradsky, A., Whiteman, K., Woodward, T., and Smith, N. (2016). Modern methods of construction: Views from the industry. NHBC Foundation. Available online: www.nhbcfoundation.org/publications/. Accessed 1 May 2019

Seebacher, S. and Maleshkova, M. (2018). A model-driven approach for the description of blockchain business networks. In Proceedings of the 51st Hawaii International Conference on System Sciences.

Slaughter, E. S. (1998). Models of construction innovation. Journal of Construction Engineering and management, 124(3):226–231.

Söderberg, J. (2015). Hacking capitalism: The free and open source software movement. Routledge.

Stroukal, D. et al. (2016). Bitcoin and other cryptocurrency as an instrument of crime in cyberspace. In Proceedings of Business and Management Conferences, number 4407036. International Institute of Social and Economic Sciences.

Swan, M. (2015). Blockchain: Blueprint for a new economy. O'Reilly Media, Inc.

Swan, M. (2018). Blockchain economics: "Ripple for erp". Eur. Financ. Rev, pages 24–27.

Swanson, T. (2015). Consensus-as-a-service: a brief report on the emergence of permissioned, distributed ledger systems.

Szabo, N. (1997). The god protocols. Satoshi Nakamoto Institute, retrieved online:15 Mar 2019 from nakamotoinstitute.org/the-god-protocols/.

Tapscott, D. and Tapscott, A. (2017). How blockchain will change organizations. MIT Sloan Management Review, 58(2):10.

Turk, Ž. and Klinc, R. (2017). Potentials of blockchain technology for construction management. Procedia Engineering, 196:638–645.

Viriyasitavat, W., Da Xu, L., Bi, Z., and Sapsomboon, A. (2018). Blockchain-based business process management (bpm) framework for service composition in industry 4.0. Journal of Intelligent Manufacturing, pages 1–12.

Waller, D. L. (2003). Operations management: a supply chain approach. International Thomson Business Press.

Wang, S., Yuan, Y., Wang, X., Li, J., Qin, R., and Wang, F.-Y. (2018a). An overview of smart contract: architecture, applications, and future trends. In 2018 IEEE Intelligent Vehicles Symposium (IV), pages 108–113. IEEE.

Wang, W., Hoang, D. T., Xiong, Z., Niyato, D., Wang, P., Hu, P., and Wen, Y. (2018b). A survey on consensus mechanisms and mining management in blockchain networks. arXiv preprint arXiv:1805.02707.

Warne, L. (2016). Crime in the construction industry. ciob policy document, Chartered Institute of Building, Englemere, Kings Ride, Ascot, Berkshire SL5 7TB, United Kingdom.

Waterhouse, R., Bew, M., Parkinson, K., Malleson, A., May, I., Matthews, A., Lane, R., Dodd, P., and Hamil, S. (2017). Nbs national bim report 2017. Published online. Retrieved Mar 3, 2019 from www.thenbs.com/knowledge/nbs-national-bim-report-2017.

Waterhouse, R., Highfield, B., Hamil, S., Malleson, A., Kell, A., Tate, G., Jackson, R., and Ainscough, N. (2019). Nbs construction technology report 2019. Published online. Retrieved Mar 23, 2019 from https://www.thenbs.com/knowledge.

Xu, X., Weber, I., and Staples, M. (2019). Architecture for blockchain applications. Springer.

Zyskind, G., Nathan, O., et al. (2015). Decentralizing privacy: Using blockchain to protect personal data. In Security and Privacy Workshops (SPW), 2015 IEEE, pages 180–184. IEEE.

Building Information Modelling

Towards the development of a Digital Twin: A comparative study of 3D data acquisition methods for mechanical and electrical assets

P. Linka[1], T. Kettle[1], M. Leon[2] and R. Laing[2]
[1]Return to Scene Ltd, City Wharf, Shiprow, Aberdeen, AB11 5BY, United Kingdom
[2]Scott Sutherland School of Architecture and the Built Environment Robert Gordon University, Aberdeen, UK
*email: m.leon@rgu.ac.uk

Abstract

Point clouds and photogrammetry are becoming a quasi-standard as representation tools for capturing existing assets condition and for monitoring the progress and development of new assets. This is apparent to several industries related to construction and manufacturing, including among other infrastructure and energy sectors. These industries face immense pressures to develop the Digital Twin, with significant momentum and extensive research and development being currently undertaken on this topic, focusing on technologies, processes and projects' requirements.

Existing software and online systems and platforms are currently available that can host and integrate the 3D collected data with cloud-based database applications, allowing projects' sharing, viewing, delivery and operation of the assets; these systems are being defined as Visual Asset Management (VAM) solutions. VAM systems can also provide a platform that integrates multiple visual data sources, including Building Information Modelling data, associated asset documentation and photographic records of the assets. Commercial projects that aim to develop a digital twin, focusing primarily on small scale mechanical and electrical assets reverse engineering processes, often utilize faster approaches to 3D data acquisition, like photogrammetry, for cost control and efficiency. However, these types of projects frequently require advanced levels of accuracy that is not often achieved with conventional 3D data acquisition methods.

The research contribution and innovative aspects of this research are focused on conducting a comparative study between the application of multi-image spherical photogrammetry (MISP), a process not typically utilised in 3D data collection, 3D scanning and total station data for very high-accuracy 3D data collection of small scale assets, thus gaining in speed of data collection. The case study involves an Oil and Gas Training Facility, in Aberdeenshire UK, where both a qualitative and quantitative analysis will be undertaken for comparing the 3D collected data. Based on this comparison, an evaluation of the 3D data collection techniques and methods is compiled, followed by the analysis of the developed point clouds. According to that, indicators are proposed to support decision making in terms of accuracy, level of detail and suitability for smaller scale and highly technical projects.

The findings demonstrate that spherical photogrammetry and 3D laser scanning can be used independently or in combination, depending on the project specifics, for ensuring assets accuracy and reliability of information for operations and maintenance, with the parameters of clients' requirements, quality, time and cost having a significant impact on the level of detail that can be provided.

This project proposes a step change in how we consider 3D data acquisition for technical and small-scale projects with a broader impact on developing reverse engineering processes for achieving the Digital Twin.

Keywords: Digital Twin, Multi-Image Spherical Photogrammetry, 3D data collection, M&E.

1. Introduction

The 4th Industrial Revolution claims to deliver the much-desired continuum between digital and physical spaces while blurring the boundaries between real and virtual environments, thus bringing a paradigm shift in the ways we work, manage and operate assets (Leon et al., 2017; Laing 2019). Achieving this digital revolution for existing assets requires advanced reverse engineering methodologies, employing three-dimensional data capturing processes (Cataluci, 2018; Hanza, 2015; Altuntas, 2015; Pagani, 2011). Factors which influence the choice of 3D capturing methods including the scale of the asset, the type of use, the space complexity and end users' requirements (Altuntas 2015).

This research explored the initial stages of developing a Digital Twin, by investigating three different 3D data capture techniques, within the context of a complex mechanical and electrical (M&E) facility. The data capture methodologies compared within this case study include photogrammetry, HD laser scanning and total station data, where a comparative analysis is implemented.

Previous research indicates that terrestrial laser scanners are not necessarily the most appropriate method when the assets include complex details, due to surfaces being blocked by other items (Altuntas, 2015), where photogrammetry was suggested as the best method to record any obscured areas. As a result, both 3D scanned, and photogrammetric point clouds are merged and integrated into a common coordinate system. This research expands on that in the literature and examines the accuracy and applicability of following data capture methods: 3D laser scanning, spherical photogrammetry and still images for the M&E assets. The significance of this research pinpoints the importance of an accurate 3D data collection for developing a Digital Twin of an asset, especially when it comes to applying reverse engineering processes for M&E facilities.

2. Literature Review

Construction and Infrastructure industries are nowadays focusing more and more on the application of Building Information Modelling (BIM) technologies and processes with numerous publications presenting the impact and benefits on projects life cycle (Arayici, 2008; Volk, Stengel, & Schultmann, 2014; Edirisinghe, London, Kalutara, & Aranda-Mena, 2017). Arguably, this research showcases that BIM is still widely underutilised (Hosseini, Roelvink, Papadonikolaki, Edwards, & Pärn, 2018; Orr, Shen, K Juneja, Snodgrass, & Kim, 2014) as it requires a substantial paradigm shift in the ways we approach projects, starting with the end in mind (Re Cecconi, Maltese, & Dejaco, 2017). Nevertheless, other industries, including Manufacturing and Energy sectors, are very well aware of this concept, which is highlighted with the application of reverse engineering processes (Herráez, Martínez, Coll, Martín, & Rodríguez, 2016). The epicentre of reverse engineering lies in recreating a product or asset based on real-life data, where models can be created by utilising 3D data capturing methods followed by 3D reconstruction (Bénière, Subsol, Gesquière, Le Breton, & Puech, 2013). With the current speed of technological developments and Internet of Things, it is only a matter of time to have smart digital "copies" of any scale of assets, including entire cities (Schamp, Hoedt, Claeys, Aghezzaf, & Cottyn, 2018; Rosendahl, Schmidt, Luder, & Ryashentseva, 2015).

2.1 Gap in knowledge

The use of laser scanning and photogrammetry as a method for reality capture has been well documented in the literature (Altuntas, 2015; Fadli, Barki, Boguslawski, & Mahdjoubi, 2015; Faltýnová, Matoušková, Šedina, & Pavelka, 2016; Pejic, Krasic, Krstic, Dragovic, & Akbiyik, 2017; Ostrowski, Pilarska, Charyton, & Bakuła, 2018; Daneshmand et al., 2018). Despite an extensive previous research on 3D data capturing techniques, a significant research gap still exists in establishing the accuracy of the methods (Randall & Philp, 2013; Dai, Feng, & Hough, 2014), especially in relation to the multi-image spherical photogrammetry (Fangi 2007; Pagani 2011), an approach not typically utilised for 3D data collection, and their suitability for specific types of projects and environments (Daneshmand et al., 2018).

2.2 Total station, 3D laser scanning and photogrammetry

Prior to comparing the 3D data acquisition methods, it was necessary to define two major terms and factors influencing the data capture process of an asset, that is resolution and accuracy. The definitions below are applicable during this research:

- Resolution is a measure intrinsic to the capture device, as it measures the minimal distance between two distinct data samples; these samples consist of points in the case of laser scanning and pixels in the case of photogrammetry (Fadli et al., 2015).
- Accuracy is the difference between the measured sample coordinates and the real physical coordinates of that sample in the captured scene (Fadli et al., 2015).

These factors cannot be separated, as the data resolution and accuracy of a 3D captured sample depends on the range or the distance of the corresponding physical sample from the capture device.

Regarding the various technologies currently utilized for data capture and measurement, these typically include 3D laser scanning, photogrammetry and the use of total station. Total station for example, is recording individual points by measuring the inclined (slope) distance to the object, as well as two angles (horizontal and vertical), which ultimately makes it possible to calculate individual point coordinates. Nevertheless, the quality and accuracy of measurements of modern electronic surveying instruments such as total station may be affected by capacity of the instrument battery, surface material, colour and variations in light conditions (Beshr & Abo Elnaga, 2011).

Photogrammetry works with the use of digital still images stitched together (Daneshmand et al., 2018), and spherical photogrammetry with the use of spherical photographs, overlaid and connected from multiple images or lenses images (Fangi 2007). Even though extensive research has investigated the comparison of 3D scanning with traditional photogrammetry, showcasing a good level of accuracy with both methods (Altuntas, 2015; Siebke et al., 2018), little has been done to examine the application of spherical photogrammetry. The critical difference between traditional photogrammetry and spherical one is focused on the time required to collect the data and the number of positions for thorough asset capture. Although both methods use cameras for data collection and the collected images are aligned by use of structure from motion or multi-view stereo algorithms, the processing and information gathering time differs significantly, in favor of spherical photogrammetry (Pagani 2011; Sapirstein 2016).

In terms of data application, the use of photographic surveys and laser scanning can provide the geometry for creation of models such as: building information modelling, digital elevation modelling, digital surface modelling, digital terrain modelling and, most importantly, for the creation of digital twins (Moon et al., 2019; Woodhead, Stephenson, & Morrey, 2018). Importantly, Terrestrial Laser Scanning (TLS) is often used in addition to photogrammetry, offering high accuracy geometric data achieved in fast, accurate and flexible manner (Laing 2019; Daneshmand et al., 2018).

2.3 Accuracy issues

Even though the technologies described above include different degrees of accuracy and are typically well-trusted within the construction and infrastructure industries, issues of misalignment and data accuracy are an often encountered, depending on several technical aspects, for example, type of equipment, environmental conditions, quality of lenses, etc. Such errors can cause major issues, especially in assets where high levels of accuracy are required (i.e. M&E equipment).

Moon et al. (2019) conducted an accuracy test for Terrestrial Laser Scanner application with 3D point cloud data collection and photogrammetry application, where the 3D point cloud data were obtained from 2D images. Targets were used to increase the accuracy of the image processing and coherence with the laser scan data. Overlaying data captured by both methods was followed by point matching registration to increase the data coherence. Findings of this study recommended accuracy improvement by combining the scan data with photogrammetry-based point cloud data by creation of the hybrid point cloud where the data distribution below 10 cm was found to have improved from 82.723% to 86.604% (Moon et al., 2019). This research also indicated that where the data distances were large, error arose due to blind spot that occurred during the laser scanner data acquisition.

Another approach to the creation of 3D models by applying surface reconstruction has been presented by Barazzetti et al., (2018). Their experiment involved spherical photogrammetry and use of low cost 360° cameras for asset capture. Automatic generation of 3D model via image-based modelling algorithms was performed using Agisoft PhotoScan (Agisoft Photoscan Pro, 2019) and Pix4Dmapper software (Pix4Dmapper, 2019). Using the ground sampling distance, 6 targets were measured with Total Station and compared to the obtained photographs. The results show 2.5mm discrepancy with the 360° images being three times worse. Despite the findings, Barazzetti et al. (2018) suggest that spherical photogrammetry is beneficial and more suitable in regard to the field of view and image overlap as well as for the use in limited space or where the prompt documentation is required. This paper is re-examining the spherical photogrammetry (Fangi, 2007), which is not yet widely utilized to date, due to limited data processing software available on the market, and proposes an innovative approach in relation to data capture constrains.

3. Methodology

As part of this comparative study, we conducted a series of field tests to identify the differences between three different 3D data acquisition methods used to create a digital twin of an asset; these included total station data, terrestrial laser scanning (LS) and multi-image spherical photogrammetry (MISP). The comparative methodology utilized to test the accuracy of different 3D data acquisition methods was adapted from Sapirstein (2016) who applied a similar approach to evaluate traditional photogrammetry over terrestrial laser scanning.

Regarding the study context, the surveyed site is an Oil and Gas Training Facility, in Aberdeenshire, UK, which is representative of a highly technical infrastructure and M&E environment. Following the data collection, the data were compared and evaluated with the application of a number of parameters, including survey time, image quality, point cloud quality and most importantly, data accuracy.

3.1 3D data collection

This research is evaluating the levels of accuracy between different 3D data collection methods and for that purpose, it was essential to set up a control coordinate system that both data collection methods could be registered to and quantified against. The "true" 3D coordinates that we would compare both the laser scanning and PG were set out using a total station. The control network that was set out using the Total Station consisted of 25 targets transformed into a site coordinate system. Five of the targets from this were then used as Ground Control Points (GCP) to register both surveys methods to the same coordinate system, leaving 20 targets that were used to compare the recorded 3D position from each survey (Figure: 1). These targets would not be used during the process of registration and alignment to simulate a simple capture done without more advanced survey techniques (Sapirstein 2016).

On the day of the survey, the targets were set out first in a geometric design to create an optimum control network for the site. Two surveyors then conducted the Total Station survey of these targets while a third one started the multi-image spherical capture. The Laser 3D Scanning capture started after the total station survey, and it was followed by the Multi-Image Spherical Photogrammetry (MISP) survey. We also created a grid for positioning the equipment for optimal results. The details of how each method was applied are presented in Table 1.

The laser scanning survey was conducted using a Faro Focus x150, which has an internal accuracy of 3mm up to a distance of 70m away (Faro Focus x150 Tech Sheet). Twenty-two positions were scanned over the site, each with a panoramic spherical image (Figure: 1). These were then registered in Faro Scene software (Faro, 2019) using the Top View-Based and Cloud to Cloud automatic techniques.

The software registration report recorded a mean point error of 2.1mm and a maximum point error of 4.1mm. After the registration was completed, the project was transformed into the coordinate system set out using the 5 GCP. The location of the other targets was automatically detected by the software, which was recorded for comparison. The automatic detection was used to reduce manual error. A final project point cloud was also exported to PTS file format for comparison purposes afterwards.

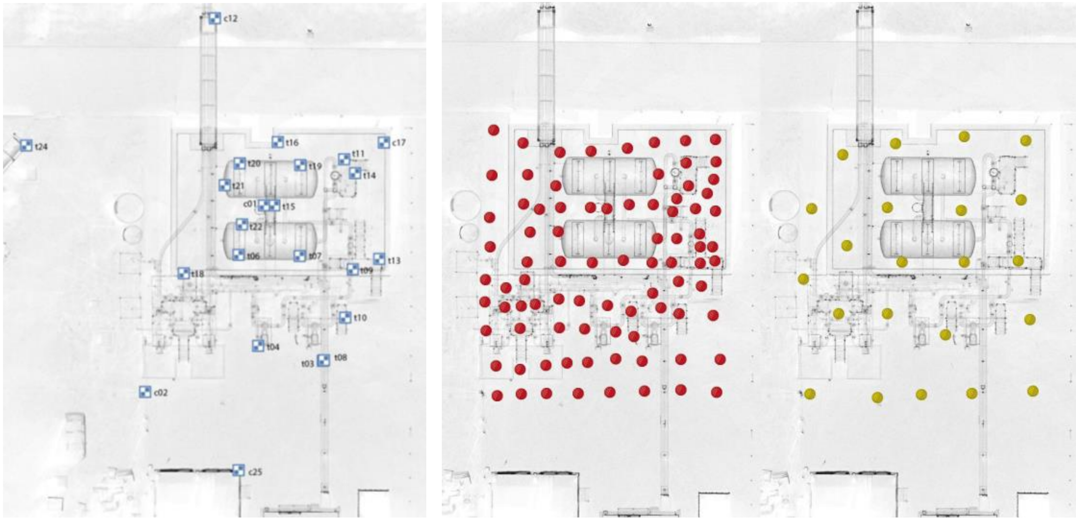


Figure 1: Location of the targets placed at the survey site and location of positions captured by the MISP and laser scanning survey techniques

Table 1: Details of the survey using both techniques, Laser Scan & Multi Image Spherical Photogrammetry

	laser scanning	*MISP*
Survey time (Hr)	*05:03*	*04:04*
Positions	*22*	*87*
Spherical Images	*22*	*172*
Spherical Image size (pixels)	*10142 x 5071*	*15840 x 7920*
Avg time per position	*8-15 min*	*2-3 min*
3D points in final point cloud	*29243077*	*226870132*

The photogrammetric survey was conducted using the Multi-Image Spherical Photogrammetry (MISP) technique, due to its key advantages compared to traditional photogrammetry, including the speed at which the site could be covered, completeness of the documentation and correction of image distortion by merging the images together, thus making it an ideal technique (Fangi, 2007). A Nikon D800 with a 16mm fisheye lens was used on a panoramic head to capture 360 high definition equirectangular images in 87 positions around the site (Figure: 1). The multiple exposure and directional images were merged to create a spherical image using PTGui panoramic photography software (PTGui, 2019) at a high pixel resolution to increase the possible accuracy (Fangi, 2007). The equirectangular images were then aligned together using Agisoft Photoscan Pro photogrammetric software. After alignment, the targets were automatically detected by the software and the 5 GCP used to transform to the same coordinate system. Once again, the position of the other targets was then recorded for comparison and a dense point cloud produced and exported to PTS file format.

4. Data analysis, evaluation and findings

4.1 Data Analysis

As stated at the beginning of the paper, we analysed the collected data with two separate aims: 1. to calculate the precision of points in space as recorded by laser scan and multi-image spherical photogrammetry (MISP) and 2. to calculate the precision and accuracy of measurements taken from the recorded data.

The error difference for each target form both techniques in comparison to the total station was calculated using, and subsequently, RMS (Root, Mean, Squared) error of 0.003m for the laser scan and 0.016m for the photogrammetry was recorded.

To calculate the accuracy of measurements for each technique, the distance between targets was calculated for total station, laser scanning and MISP using the same method as aim 1. The distances calculated from the laser scanning and MISP were then compared to the results from TS using it as a control to establish the error in measurement recorded in both techniques (Table 2).

Table 2: Observed Error in measurements (m) for Laser Scan and Multi Image Spherical Photogrammetry measurements

	laser scanning	*MISP*
MIN Error	*0.000*	*0.000*
MAX Error	*0.005*	*0.023*
Standard Deviation	*0.001*	*0.005*
RMS	*0.002*	*0.009*
95.5% confidence level (±m)	*0.002*	*0.008*
Precision 1:k	*n/a*	*1:3526*

Following the calculation of error for each measurement, the standard deviation, RMS and 95.5% confidence level (that measurement taken will be within the calculated error), was determined. Result of ± 0.002m for the laser scanning and ± 0.008m for MISP at 95.5% confidence level have been observed. Subsequently, the precision for the MISP was calculated in line with previous research (Sapirstein 2016), to estimate the possible error within the captured scene while removing scale. This is calculated as 1: k, where k is the size of the scene divided by the standard error. For example, a precision of 1:1000 would produce an estimated error of 1mm in the scene that is 1m long, however, would produce an estimated error of 10mm in the 10m long scene. The precision recorded for the MISP capture is 1:3526 so a scene that was 10m would expect to have an error of 0.0028m.

4.2 3D data evaluation

On inspection of the results, we identified benefits and challenges for each survey technique. MISP method allowed the capture of significantly more positions than laser scanning technique (Figure: 1), due to less time required to capture each position as presented in Table 1. Following the data processing within a visualization software, it also became apparent that the addition of more set up positions required by MISP significantly reduced the blind spots in the reality capture of the site. The MISP technique employed in the study also produced images with a greater level of detail than those recorded by laser scanning. The MISP recorded images of a 125MP compared to 52MP by the laser scanning (Figure 2).

The point clouds exported from each technique differed significantly in the number of points they had generated (Table 1) due to several factors including, the number of positions captured, the quality setting of the laser scanner and the number of features identified in the photogrammetric software. For achieving the same level of detail with the 3D points captured, the survey time would have to be significantly extended when applying 3D laser scanning. Furthermore, point clouds generated from each survey technique were reviewed in a point could visualization software (Autodesk Recap), and several differences have been identified as described below.

Laser scanning quality can appear sharper than MISP as can be seen in figure 4, due to the accuracy of laser scanning point collection and the algorithms to match the features in the spherical images. Furthermore, blind spots were present in both survey techniques; however, more of them were apparent in laser scanning than MISP. Two factors contributing to this are the number of laser scanning positions recorded and the ability for the photogrammetric software to identify features within the spherical images. A lack of line of sight created blind spots when we applied laser scanning survey, thus missing details that have to be recorded. On the other hand, blind spots are occurring with MISP when the detail that needs to be captured cannot be seen in the multiple spherical images, and the features cannot be identified by the photogrammetric process.

Figure 2: Example of Spherical images from laser scanning (top) and Spherical Photography (bottom).

Concerning the level of detail, more comprehensive and dense capture can be recorded by MISP where there are features that can be matched, in comparison to the laser scanning, where the level of detail depends on the quality setting of the laser scanner equipment and the number of scanning positions. Additionally, material properties of the surfaces that can be recorded by the previous methods also vary. The recorded properties of different materials in each point cloud also differ significantly due to the capabilities of the techniques used to capture the information. For example, laser scanning has difficulty in capturing matt black materials, where MISP struggles to record the surfaces that have no texture (lack of roughness of material) such as solid colours. When it comes to the infrastructure specifics, for example, the areas of concrete flooring have a higher level of texture, that can be identified as a feature in the photogrammetric software and will produce a higher number of points than recorded by laser scanning.

4.3 Constraints model

Overall, to ensure the best possible outcome of a survey, it is necessary to establish the aim, scope and required data quality of the capture. Following the data analysis, it is essential to select a capture method with great caution following a clear identification of priorities, requirements and purposes of the survey. Importantly, achieving a balance between factors and constraints influencing the choice of the method can be proved challenging. Figure 3 represents a proposed Iron Triangle focused on the Reality Capture, where capturing time, quantity (of points and blind spots) and accuracy (Quality of point cloud), must be taken into consideration as they highly depend on each other and can impact the overall outcome, thus representing a constrains model. Any amendments to the original scope of the capture will influence the factors mentioned in Figure 3.

Figure 3: Iron Triangle of reality capture.

5. Discussion

In order to compare 3D data collection methods and equipment efficiency and accuracy, the same data was used when tested with all the different methods as per previous research (Fadli et al., 2015), with the number of targets utilised and the data collection process impacting the quality of the results. Similarly, Shanbari et al. (2016) suggest that models and point clouds accuracy derived from photogrammetric data collection depend on the image quality; however, they cannot match the millimetre accuracy expected from laser scanners. Nevertheless, this may not be a concern as it depends on the level of accuracy and level of detail that is part of the scope for any given project. Importantly, additional research reported that photogrammetry and laser scanning techniques could be used in combination to enhance the results of the digital surveys (Boehler & Marbs, 2004; El-Omari & Moselhi, 2008; Fadli et al., 2015; Moon et al., 2019).

Moon et al. (2019) specifically, highlighted the significant accuracy improvement in the 3D point cloud data by combining output collected by terrestrial laser scanner and photogrammetry, emphasizing the complementary values of each technique with the combination of the two techniques giving the optimum results. Furthermore, this research suggested the creation of hybrid point clouds can overcome the geographic and physical limitations of laser scanning technology, an output supported by this research as well.

5.1 Conclusions

The study presented in this paper focused on establishing the accuracy and precision of the most popular surveying methods: laser scanning and spherical photogrammetry. The knowledge contribution is the use of a multi-image spherical photogrammetry method, instead of traditional photogrammetry, for improving capturing time on projects where time is limited. The study results prove the suitability of the MISP for reality capture, reverse engineering and digital twin creation. When it comes to the comparative analysis of 3D laser scanning and MISP, both methods offer different benefits but also have limitations, like the line of sight issues and surfaces texture. The research proposed a mixed methods approach that would include both MISP and 3D laser scanning, while the Iron Triangle of Reality capture can provide further support and understanding regarding constrains prioritising.

Acknowledgements

The authors would like to acknowledge the support by Innovate UK and Scottish Funding Council, Grant No. KTP011078.

References

Agisoft Photoscan Pro, (2019). *Agisoft photoscan pro.*, 2019, from https://www.agisoft.com/

Altuntas, C. (2015). Integration of point clouds originated from laser scaner and photogrammetric images for visualization of complex details of historical buildings. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-5/W4*(5), 431-435.

Arayici, Y. (2008). *Towards building information modelling for existing structures* Emerald Group Publishing Limited.

Barazzetti, L., Previtali, M., & Roncoroni, F. (2018). Can we use low-cost 360-degree cameras to create accurate 3d models? *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2*(2), 69-75.

Bénière, R., Subsol, G., Gesquière, G., Le Breton, F., & Puech, W. (2013). A comprehensive process of reverse engineering from 3D meshes to CAD models. *Computer-Aided Design, 45*(11), 1382-

1393.

Beshr, A. A. A., & Abo Elnaga, I. M. (2011). Investigating the accuracy of digital levels and reflectorless total stations for purposes of geodetic engineering. *Alexandria Engineering Journal, 50*(4), 399-405.

Boehler, W., & Marbs, A. (2004). 3d scanning and photogrammetry for heritage recording: A comparison. , *Geoinformatics 2004 Proc. 12th Int. Conf. on Geoinformatics − Geospatial Information Research: Bridging the Pacific and Atlantic University of Gävle, Sweden, 7-9 June 2004.*

Catalucci, S., Marsili, R., Moretti, M., & Rossi, G. (2018). Comparison between point cloud processing techniques. *Measurement; Measurement*, *127*, 221-226.

Cloud Compare, (2019). from http://cloudcompare.org/

Dai, F., Feng, Y., & Hough, R. (2014). Photogrammetric error sources and impacts on modeling and surveying in construction engineering applications. *Visualization in Engineering,* 2(1), 1-14.

Daneshmand, M., Helmi, A., Avots, E., Noroozi, F., Alisinanoglu, F., Arslan, H. S., et al. (2018). 3D scanning: A comprehensive survey.

Edirisinghe, R., London, K. A., Kalutara, P., & Aranda-Mena, G. (2017). *Building information modelling for facility management: Are we there yet*? Emerald Publishing Limited.

El-Omari, S., & Moselhi, O. (2008). Integrating 3D laser scanning and photogrammetry for progress measurement of construction work. *Automation in Construction, 1*8(1), 1-9.

Fadli, F., Barki, H., Boguslawski, P., & Mahdjoubi, L. (2015). 3D scene capture: A comprehensive review of techniques and tools for efficient life cycle analysis (LCA) and emergency preparedness (EP) applications. *WIT Transactions on the Built Environment, 14*9, 85-85 - 96.

Faltýnová, M., Matoušková, E., Šedina, J., & Pavelka, K. (2016). Building facade documentation using laser scanning and photogrammetry and data implementation into bim. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B*3, 215-220.

Fangi, G. (2007). The multi-image spherical panoramas as a tool for architectural survey. , *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences.* (36)

Faro, (2019). *Faroscene*., 2019, from https://www.faro.com/en-gb/products/construction-bim-cim/faro-scene/

Herráez, J., Martínez, J. C., Coll, E., Martín, M. T., & Rodríguez, J. (2016). 3D modeling by means of videogrammetry and laser scanners for reverse engineering. *Measurement, 8*7, 216-227.

Hosseini, M. R., Roelvink, R., Papadonikolaki, E., Edwards, D. J., & Pärn, E. (2018). *Integrating BIM into facility management: Typology matrix of information handover requirements*

Laing, R. (. (2019). Digital participation and collaboration in architectural design. Abingdon: Routledge.

Leon, M., Ahiaga-Dagbui, D., Fleming, C., & Laing, R. A. (2017). Exploring visual asset management collaboration: Learning from the oil and gas sector ARCOM.

Moon, D., Chung, S., Kwon, S., Seo, J., & Shin, J. (2019). *Comparison and utilization of point cloud generated from photogrammetry and laser scanning: 3D world model for smart heavy equipment planning*

Orr, K., Shen, Z., K Juneja, P. K., Snodgrass, N., & Kim, H. (2014). Intelligent facilities - applicability and flexibility of open BIM standards for operations and maintenance. , *Construction Research Congress 2014.* pp. 1951.

Ostrowski, W., Pilarska, M., Charyton, J., & Bakuła, K. (2018). Analysis of 3d building models accuracy based on the airborne laser scanning point clouds. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII*-2(2), 797-804.

Pagani, A., Gava, C., Cui, Y., Krolla, B., Hengen, J., & Stricker, D. (2011). Dense 3D point cloud generation from multiple high-resolution spherical images. *VAST 2011: The 12th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage, Prato, Italy, October 18-21, 2011. Proceedings.* Prato, Italy. pp. 17-17-24.

Pejic, P., Krasic, S., Krstic, H., Dragovic, M., & Akbiyik, Y. (2017). 3D virtual modelling of existing objects by terrestrial photogrammetric methods--case study of barutana/ kreiranje virtualnih 3D modela izgradenih objekata metodama zemaljske fotogrametrije--studija slucaja barutana.(professional paper/Strucni clanak)(report). *Tehnicki Vjesnik - Technical Gazette, 2*4, A233.

Pix4Dmapper, (2019). from https://www.pix4d.com/product/pix4dmapper-photogrammetry-software

PTGui, (2019). from https://www.ptgui.com/

Randall, T., & Philp, D. (2013). *Client guide to 3D scanning and data captur*e (Guide. United Kingdom: The Building Information Modelling (BIM) Task Group.

Re Cecconi, F., Maltese, S., & Dejaco, M. (2017). Leveraging BIM for digital built environment asset management. *Innovative Infrastructure Solutions*, 2(1), 1-16.

Rosendahl, R., Schmidt, N., Luder, A., & Ryashentseva, D. (2015). *Industry 4.0 value networks in legacy system*s IEEE.

Sapirstein, P. (2016). Accurate measurement with photogrammetry at large sites. *Journal of Archaeological Science, 6*6, 137-145.

Schamp, M., Hoedt, S., Claeys, A., Aghezzaf, E. H., & Cottyn, J. (2018). *Impact of a virtual twin on commissioning time and quality*

Shanbari, H. A., Blinn, N. M., & Issa, R. (2016). Laser scanning technology and bim in construction management education. [http://www.itcon.org/2016/14] *Laser Scanning Technology and BIM in Construction Management Education. Journal of Information Technology in Construction (ITcon), Special Issue: 9th AiC BIM Academic Symposium & Job Task Analysis Review Conference, 2*1, 204.

Siebke, I., Campana, L., Ramstein, M., FurtwäNgler, A., Hafner, A., & LöSch, S. (2018). The application of different 3D-scan-systems and photogrammetry at an excavation — A neolithic dolmen from switzerland. *Digital Applications in Archaeology and Cultural Heritage; Digital Applications in Archaeology and Cultural Heritage, 1*0, e00078.

Volk, R., Stengel, J., & Schultmann, F. (2014). Corrigendum to "building information modeling (BIM) for existing buildings — literature review and future needs" autom. constr. 38 (march 2014) 109–127]. *Automation in Construction; Automation in Construction, 4*3, 204-204.

Woodhead, R., Stephenson, P., & Morrey, D. (2018). Digital construction: From point solutions to IoT ecosystem. *Automation in Construction; Automation in Construction, 9*3, 35-46.

Towards a BIM-based Decision Support System for rapid generation and evaluation of holistic renovation scenarios

Aliakbar Kamari[1], Carl Schultz[1], and Poul Henning Kirkegaard[1]
[1]Department of Engineering, Aarhus University
* email: ak@eng.au.dk

Abstract

Recent research in building renovation seeks methods for the development of more holistic renovation scenarios that live up to a broader set of sustainability objectives and criteria, and that are involved in the earlier stages of the design process. One decision to be made by stakeholders is what and how a renovation scenario can be developed that fulfills various types of competing criteria and sub-criteria attached to the sustainability in its whole sense such as investment cost, energy consumption, indoor thermal comfort etc. Building Information Modeling (BIM) has the potential to aid designers in providing the required geometrical and analytical data of an existing building 3D model to select and evaluate the proper type of renovation actions during the early design stage and to make decisions that have a significant impact on the life cycle of the renovated buildings.

This paper presents a methodology for the development of a BIM-based decision support system, named PARDIS (Process integrAting Renovation DecIsion Support), which generates and evaluates optimal and holistic renovation scenarios tailored towards dwellings. PARDIS supports the renovation sector with the following features: (a) optimizing the selection process of renovation alternatives, and the generation of renovation scenarios, through specific renovation typologies and constraints, (b) evaluating standard sustainability Key Performance Indicators - KPIs (e.g. energy consumption, investment cost, indoor thermal comfort, indoor air-quality etc.) over the generated renovation scenarios, as well as (c) visualizing the generated renovation scenarios for ease of comprehension by the designers, and for enabling discussion between expert stakeholders (i.e. architects, engineers, contractors etc.) and non-expert stakeholders (i.e. building occupants, owners etc.). As such, PARDIS supports informed decision making in early design for the development of optimal renovation scenarios. The first prototype of the PARDIS Revit plug-in is demonstrated in this paper and empirically evaluated on a large apartment block in Denmark). Likewise, the tool's outcome is explored through a focus group workshop with practitioners in Aarhus, Denmark. For further clarification of the potential use of PARDIS related to the studied case, the tool's application is discussed with three BIM specialist-architect engineers (from different consultancy corporations).

Keywords: Sustainable Building Renovation, Holistic Renovation Scenarios, Decision Support Systems (DSS), Integrated Design (ID), Building Information Modeling (BIM).

1. Introduction

Research on the barriers for building renovation in Denmark has revealed that an important obstacle is a lack of simple and holistic tools that can assist stakeholders in prioritization and decision-making during the early stages of building renovation projects (Jensen et al., 2015). In developing renovation scenarios through an integrated schema in early design stages (Kamari et al., 2017a), designers and especially architects tend to look for different design solutions before going in depth into one fixed theme of solutions However, engineers are much more likely to be content with finding one possible solution and sticking to it without investigating other possible solutions that might be valuable (Akin 2001). According to Rice (1996), once a solution appears to solve the problem for an engineer, she/he is not willing to change it. Rice (1996) adds that it is characteristic for engineers to come to only one conclusion in design since they are working with objective parameters. On the other hand, contractors and owner preferences embraces a rapid exploration of various concepts and solutions in terms of budget and period, primarily focusing on the construction cost and construction period.

This paper presents a methodology for the development of a BIM-based decision support system (BIM-based DSS), named PARDIS (Process integrAting Renovation DecIsion Support), which can be used in an integrated renovation design schema (2019a) to generate and evaluate optimal and holistic renovation scenarios for the renovation of dwellings. PARDIS is structured to support the renovation sector with the following features:

a) optimizing the selection process of renovation alternatives, and the generation of the renovation scenarios, through the use of specific renovation typologies and constraints,
b) evaluating standard sustainability Key Performance Indicators - KPIs (e.g. energy consumption, investment cost, indoor thermal comfort, air-quality etc.) over the generated renovation scenarios,
c) visualizing the generated renovation scenarios for ease of comprehension by the designers, and for enabling discussion between expert stakeholders (i.e. architects, engineers, contractors etc.) and non-expert stakeholders (i.e. building occupants, owners etc.) towards making an informed decision about the most appropriate and optimal renovation scenario in a short time frame.

Building Information Modeling – BIM (Eastman et al., 2011) aids designers by providing salient 3D geometric and analytic data about the building, thus enabling designers to select and evaluate renovation actions during earlier stages of design, and to make decisions that have a significant impact on the life cycle of buildings under renovation. While shifting into the BIM framework encompasses various advantages of using a BIM-model (Becerik et al., 2010) upon all the stages of the building renovation process (from design to construction and operation phases), development and application of a BIM-based DSS (Nielsen et al., 2016; Volk et al., 2014; Schlueter et al., 2009; Jalaei et al., 2015; Kim et al., 2015; Kamari et al., 2018a,b) can specifically be exploited during the early design stages of renovation projects where a decision has a strong impact throughout the rest of the process and thus final decision-making. As such, it increases the likelihood that the owners' project goals will be met and streamlines the stakeholders' communication, collaboration, and cohesion, towards facilitation and development of holistic, optimal, and sustainable renovation solutions in a significantly reduced period.

The key contribution in this paper is the development of a plug-in for Autodesk Revit that architects or engineers can use on an existing BIM-model to invent, animate, and assess the enormous number of potential renovation scenarios, through an integrated design schema. After selecting a renovation scenario, the PARDIS Revit plug-in is intended to demonstrate the scenario by proposing the renovation changes in preparation to support the decision process. This paper builds upon our previous work related to the ReVALUE[1] research project concerning the development of a rapid constraint-based renovation design support framework through the application of a formal (logic-based) domain specific renovation modeling language (see Phase 2 in Figure 1), that enables architects and engineers to readily express their project-specific renovation design space at a range of abstraction levels. In this paper, the first prototype of the PARDIS Revit plug-in system is demonstrated and empirically evaluated on an apartment block that is renovated as phase one in an extensive transformation of a larger residential area in Aarhus, Denmark.

[1] http://revalue.dk./?page_id=196

2. Methodology

Revit dominates the Danish market based upon a survey made by BIPS (2015), and therefore is selected as the platform for development of the PARDIS. The developing plug-in is intended to rapidly generate and evaluate optimal and holistic renovation scenarios for the renovation of dwellings. In addition, the most suitable user or pilot for the tool is considered to be an Architect or Architect Engineer who is a Revit-user. Figure 1 presents the development process of PARDIS through an implementation of six specific activities or tasks as well as the tool executing process phases. The map is drawn based on a set of core elements according to the Business Process Modelling Notation – BPMN[2]. It therefore includes the tool application and executing process. The information about the implementing activities or tasks have briefly been presented in Figure 1, and the activities' focus is implementation of the tool's main programing or code blocks using the Revit Application Programming Interface (API) and Software Development Kit (SDK), besides Visual studio and C# programing. The tool executing process encompasses one plus seven (1 + 7) phases. Each phase is briefly described below.

Phase 0 requires the development of as-built 3D BIM-model of the existing building in Revit. The 3D model includes the basic elements of buildings (such as walls, windows, floors etc.), where the quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs. According to the "2019 Level of Development - LOD Specification" released by BIMForum (2019), the requirements for development of the as-built 3D BIM-model for the application of the developing tool in this paper in Revit needs to be aligned with a BIM LOD 300 (for further info. see BIMForum, 2019).

Phase 1 comprises the extraction of the required data from the developing 3D BIM-model in Phase 0. The data consists of essential geometry information that later are exploited to calculating, i.e. the investment cost or energy consumption when running simulation on the generating renovation scenarios. The data such as the heated floor area, the exterior wall area, the windows area, the roof area, the height of the building, the orientation etc. This is done by firing-up the tool within the Revit, and picking-up a room or apartment. The extracted data are displayed in the tool, which enables the user to control them constantly. Figure 2 demonstrates the tool's user interface developed as a plug-in to Revit.

Phase 2 embraces the system for the generation of holistic renovation scenarios. The term 'holistic renovation scenario' in this paper is adopted from (Kamari et al., 2018c). It serves to underline a holistic approach where various renovation objectives (i.e. energy consumption, indoor thermal comfort etc.) linking to the sustainability in its full sense (Kamari et al., 2017b) are achieved in a balanced way, through the development of a renovation scenario. A 'renovation scenario' refers to a set of particular design changes that will be made to a building, e.g. replacing all north-facing windows with triple glazing, adding a new cladding system (i.e. composite panels), and HVAC equipment.

Figure 3 illustrates the workflow of the scenario generation system that has been discussed and presented by the authors in (Kamari et al., 2019b,c), on the development of a rapid constraint-based renovation design support framework through the application of a formal (logic-based) domain specific renovation modeling language, named NovaDM (Kamari et al., 2018d). First the design team specify the (a) project-specific renovation alternatives in the form of a NovaDM action tree, (b) renovation scenario constraints, and (c) the BIM-model of the design to be renovated. The scenario generator parses the action tree into Answer Set Programming (ASP) facts and generates (optimal) scenarios that are consistent with the given constraints using the ASP reasoning engine Clingo (Gebser et al., 2016).

In addition, the scenarios are built on the basis of different constraints, primarily related to the renovation depths and level of interventions that illustrate the impact of different ambition levels concerning the European environment and economy (TECNALIA, 2015; EU, 2016). The depth of renovation refers to the extent and size of measures applied, as well as to the level of resulting energy and emissions reduction. It is used to generate scenarios with various depths of renovation including *Minor*, *Moderate*, *Deep*, and *Nearly Zero Energy Building – NZEB.*

[2] https://cloud.trisotech.com/bpmnquickguide/

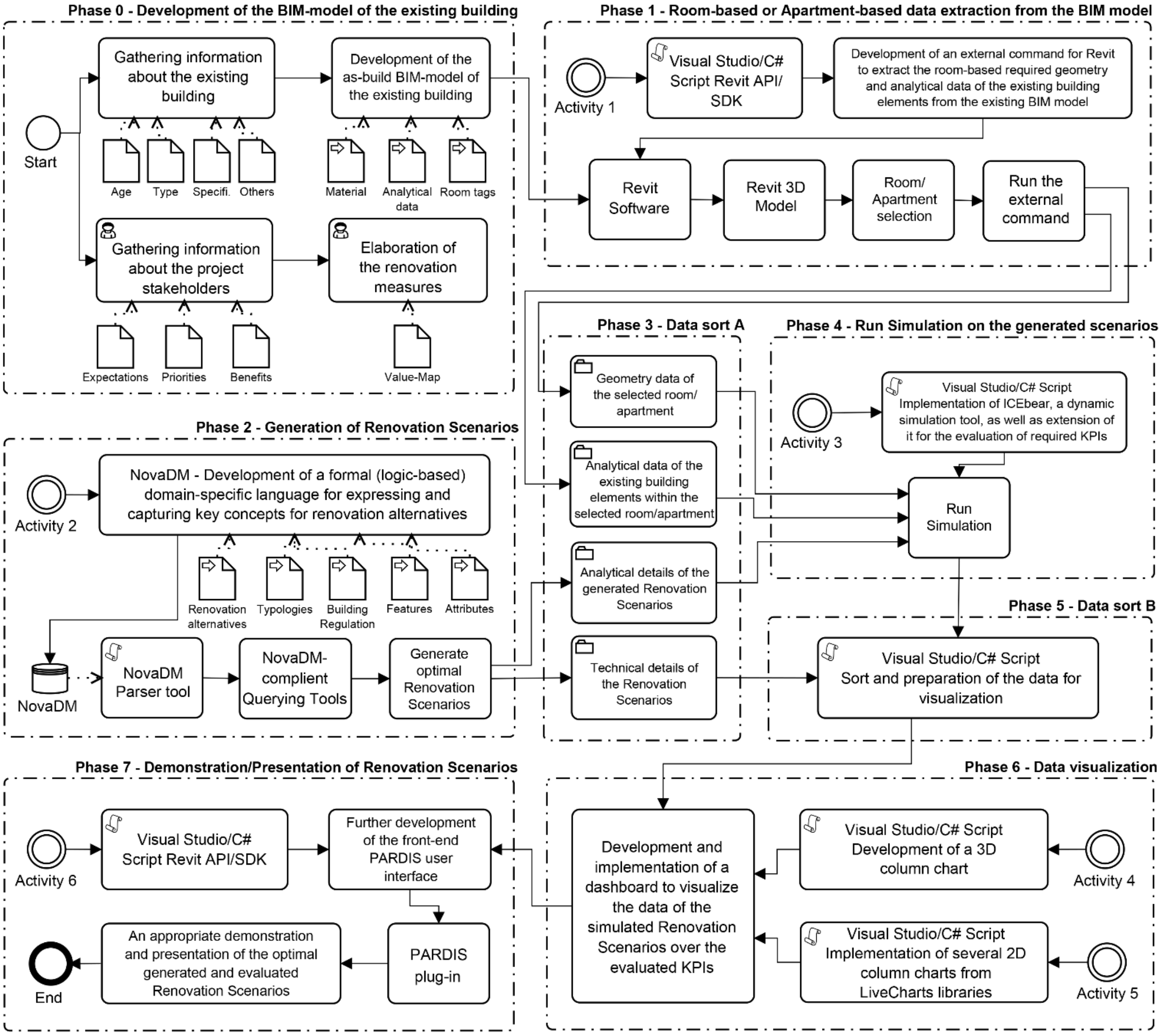


Figure 1. The development process of PARDIS as a plug-in to Revit

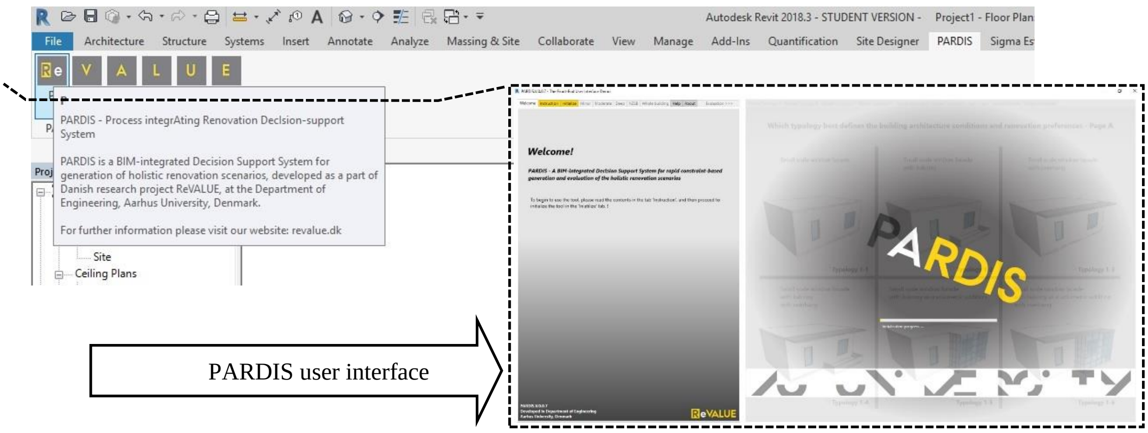


Figure 2. The PARDIS front-end user interface developed as a plug-in to the Autodesk Revit[3]

The second level of constraints link to the typologies of the existing building according to TABULA (2015). Likewise, the third level of constraints target the architectural aspects and the

[3] A video of the PARDIS first prototype can be watched in the following link: https://www.youtube.com/watch?v=u7ITPqlAiVE&feature=youtu.be

appearance of the renovation scenario (Boeri et al., 2014), especially related to the buildings' facades.

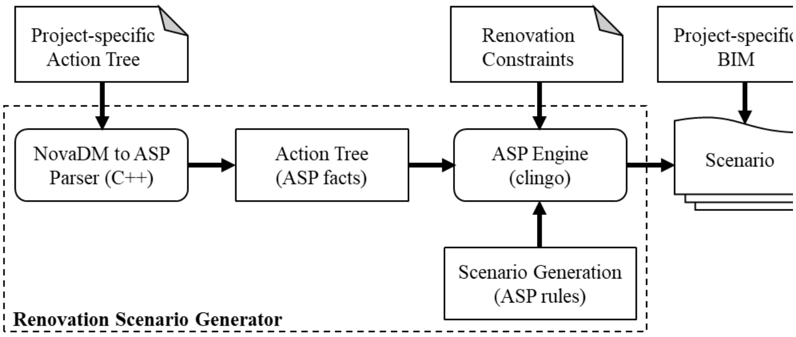


Figure 3. Workflow of the renovation generation system

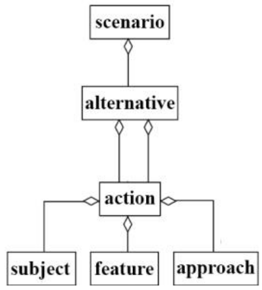


Figure 4. The relationships between concepts in NovaDM

As demonstrated in Figure 4, the scenarios are structured through the use of various layers and concepts including: *Renovation Approach*: the way that the subject will be renovated, e.g. repair, replace, remove, refurbish, or modify; *Renovation Feature*: the aspect of the subject being renovated, e.g. window frame material. Features have types (e.g. material) and values (e.g. fiberglass, uPVC, etc.); *Renovation Action*: an instance of a subject, an approach, and a set of feature types and values, e.g. "window frames will be replaced with fiberglass material"; *Renovation Alternative*: the set of (mutually exclusive) actions for a given subject, e.g. all the ways that windows can be renovated according to the specified approaches and features; *Renovation Scenario*: a set of actions such that each action belongs to a different alternative, e.g. one action for windows and one action for floors.

For each renovation project, the design team needs a way of specifying the particular subjects, features and approaches that are available. For this, a formal action tree language for compactly specifying sets of actions is developed (adopted from Kamari et al., 2019c). Each action tree (see Fig. 5) corresponds to a renovation alternative. Traversing an action tree corresponds to generating an action in a scenario, starting from the root node. Each node assigns zero or more aspects (subject, feature or approach) to the action. Tree nodes can be either xor-nodes "-" (meaning that the current action must be built by traversing exactly one child), or and-nodes "+" (meaning that the current action must be built by traversing all children).

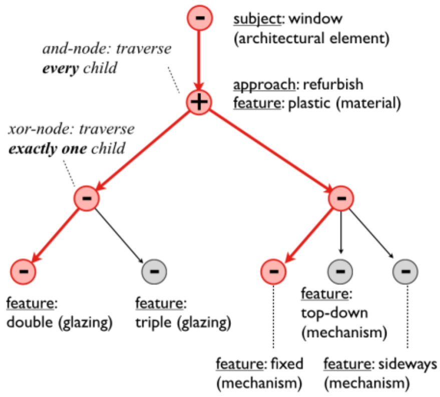


Figure 5. A NovaDM action tree

Phase 3 focuses on customizing and sorting the data outcomes from the Phases 1 and 2. Hereafter, the geometry information and the generating scenarios' data are customized and prepared to pipe into the simulation tool in the next phase.

Phase 4 includes the use of an extended version of the hourly dynamic simulation tool ICEbear. Each generated scenario in Phase 2 is then evaluated according to user-specified sustainability Key Performance Indicators - KPIs such as energy consumption, indoor thermal comfort, daylight comfort etc. ICEbear is a tool that strives to facilitate design buildings for architects and engineers, evaluating the impact of the geometry on the indoor climate and energy demand at the same time. It is based upon algorithms for auto-generating hourly building performance data at a room level basis. Table 1 summarizes the evaluating KPIs for generated renovation scenarios in this study.

Phase 5 focuses on customizing and sorting the data outcomes from the Phases 3 and 4. Hereafter, the technical details of the generated scenarios besides the outcome of the running simulation on the generated scenarios pipe into the visualization dashboard in the next phase.

Phase 6 consists of the data visualization dashboard for the mentioned evaluating KPIs. It includes one Interactive 3D bar chart custom control in WPF, besides several basic row, dynamic column charts.

Table 1. Outline for the selecting KPIs for evaluation of the generating renovation scenarios

KPIs	*Evaluation [value measurement]*
Energy consumption (Danish Energy Agency, 2017)	Reduction of energy consumption for heating measured in kWh/m2/year [less better]
Energy frames defined in BR18 (Danish Building Research Institute,2017)	Renovation energy classes (I and II) in kWh/m2/year [less better]
Indoor Thermal Comfort (Dansk Standards, 2007)	% in Class I, II, III according to EN 15251 [bigger better]
Discomfort hours above 27 and 28 (°C) (Dansk Standards, 2006)	Number of hours [less better]
Indoor Air Quality – IAQ (Dansk Standards, 2013)	% out of Class III according to EN 15251 [less better]
Investment Cost, (Molio, 2016)	Price of the procurement in DKK (Danish Krone) [less better]
DF (daylight factor), (VELUX, 2016)	$0<DF<5$ [bigger better]
Daylight according to BR18 (Danish Building Research Institute, 2017)	% ≥ 10 [bigger better]
View-out quality and Degree of privacy	% of openings area on façade regarding adjacent buildings [client dependent]
Degree of Satisfaction, (Xu et al., 2018)	% regarding effects of building space and thermal and luminous environments on satisfaction with Indoor Environment Quality – IEQ. [bigger better]
Health & Well-being, (Norback et al., 2014)	% regarding Energy improvement, indoor thermal comfort, air quality and their effects on Asthma, Allergy, and Eczema diseases [bigger better]

Phase 7 focuses on a suitable demonstration and presentation of the generated and evaluated scenarios ensuring that the outcomes are easy to be read, understood, and exploited in an actual renovation context by the involved stakeholders.

At the time of writing the present paper, the first six phases of the tool have been developed and implemented, and we are currently developing Phase 7 by interviewing and collecting data from the active practitioners within three leading architecture and engineering consultant corporations in Aarhus, Denmark.

3. Case Study – Residential Danish Buildings

In this section we present a case study where we empirically evaluate the PARDIS tool by applying it to real renovation tasks. The selected case study is a competition entry for renovation of an apartment block located in Aarhus, Denmark (see Figure 6). The apartment block is one of three so-called pilot projects, which are renovated as phase one in the extensive transformation of a larger residential area.

Figure 6. The apartment’s section plan, east and west elevations located in Aarhus, Denmark

The competition call included renovation of the building envelope, bathrooms and staircases, transformation of the ground and first floors into new two-storey dwellings as well as the addition of new dwellings above a road "cutting through" the building. For the explanatory purpose of this paper, we focus on the renovation of one representative dwelling. The target budget for the renovation of the building block was 92 million Danish kroner.

For renovation purposes in this case study, after conducting some meetings with a team of architects, engineers, and clients finding out about their priorities besides following the regulations from the municipality of the region, the tool was firstly used for preliminary evaluation of what possible renovation approaches can be included in the developing renovation scenario that meet the initial budget. That especially encompassed the renovation of roof, balcony, stairs, and new HVAC equipment, beside renovation of the façade. Next, the tool was used to generate four renovations scenarios, each relevant to different level of intervention (or so called *minor*, *moderate*, *deep,* and *NZEB* – see TECNALIA, 2015), investigating their cost, which we refer to *investment cost*.

In order to evaluate PARDIS and the data visualization approaches, we conducted a workshop with a focus group of eight practitioners from three large scale architecture consultancy companies, AART architects, Friis & Moltke, and Cebra, in Denmark. As such, the tool's outcome was presented through three visualization prototypes, a *Bullet graph*, a *Radial Chart*, and a *Heatmap*. Figure 7 demonstrates the visualization prototypes.

Participants reported that PARDIS was helpful so as to increase the awareness of the involved parties via demonstration of the *energy efficiency* (or *reduction of energy consumption), indoor thermal comfort*, and *indoor air quality* evaluation of the renovation scenarios. After the architects developed entirely new interior designs, after exploring the previous architects' proposals and adding the required changes to the existing 3D model, PARDIS was particularly used and was considered very helpful for providing a comparison addressing the *degree of privacy, degree of satisfaction, daylight condition*, and the scenarios' contribution towards creating a more *healthy* environment. The strong point about the tool application in this experience was speed towards generating and evaluating the various renovation scenarios. While the BIM specialists' experience with the tool into the current design process was overall satisfactory, the following points were stated:

- Due to the fact that the application of PARDIS and similar conceptual tools is not very commonly experienced in the current practice of renovation, it is difficult to evaluate how best it can improve the context
- The outcome as the demonstration of evaluating KPIs needs further development to support the decision into the process
- The tool is yet unable to respond to the architectural needs and alterations regarding the need for form and geometrical changes
- The fact that the tool is capable of conceptualizing and generating renovation scenarios in a very short time (max five minutes per generation and evaluation of 50 renovation scenarios per each case) is very strong and desirable aspect
- The tool successfully negotiates the present unresolved potential of integrated design and collaboration between architects, engineers, contractors, and owners in the early stages of a renovation project
- The tool should provide a comparison result for the generating and evaluating scenarios between two or more different apartments
- With further development and streamlining regarding its limitations, the tool can significantly support the involved stakeholders in the renovation process

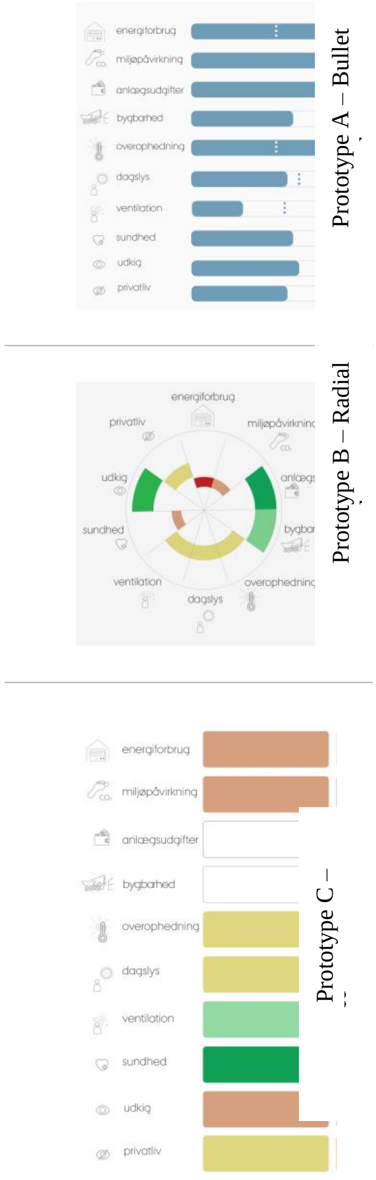


Figure 7. PARDIS visualization prototypes

4. Conclusion

This paper presented an overview of a BIM-based DSS named PARDIS for rapid generation and evaluation of the holistic renovation scenarios. PARDIS can specifically be exploited during the early design stages of renovation projects where a decision has a strong impact throughout the rest of the process and thus the final decision-making. As such, it increases the likelihood that the owners' project goals will be met and streamlines the stakeholders' communication, collaboration, and cohesion, towards facilitation and development of holistic, optimal, and sustainable renovation solutions in a shorter period. Although the tool has been developed for the renovation of dwellings or residential buildings, the flexible employed database can be extended further to include extra renovation approaches and parameters to be applied for other building types, i.e. offices or commercial buildings.

PARDIS is a significant departure from existing optimization approaches in renovation design. Existing approaches and systems tend to deliver a small number of similar, optimal designs with no intermediate layers of abstraction, and no support in analyzing and exploring the diversity of the design space. In future work we will extend PARDIS to support renovations that change the building morphology under constraints (Kondyli et al. 2017; Schultz et al. 2017) and spatial reasoning (Walega et al. 2017; Bhatt et al. 2012; Bhatt et al. 2011).

An important limitation of this research is that the tool has only been tested on a few renovation cases, and regarding the Danish context, and this is a certain aim in the future research work. In addition, the future research work concerns examination, studying, and surveying of the actual renovation context improving the PARDIS user interface especially the demonstration and presentation of the generated and evaluated renovation scenarios where the involved stakeholders and on the top of that design team is enabled to read, understand, and use the outcomes sophistically and appropriately.

Acknowledgements

The authors of the paper would like to show their gratitude to the Danish Innovation Foundation for financial support through the RE-VALUE research project.

References

Akin, Ö. (2001). Variants in design cognition. In C. Eastman, M. McCracken, & W. Newstetter, eds. Design Knowing and Learning Cognition in Design Education. Oxford: Elsevier, 105–124.

Becerik-Gerber, B., & Rice, S. (2010). The perceived value of building information modeling in the U.S. Building Industry. Journal of Information Technology in Construction, Vol. 15, 185.

Bhatt, M., Schultz, C. & Huang, M. "The Shape of Empty Space: Human-Centred Cognitive Foundations in Computing for Spatial Design". In: VL/HCC 2012: IEEE Symposium on Visual Languages and Human-Centric Computing. Innsbruck, Austria, 2012, pp. 33–40.

Bhatt, M. Lee, J.H. & Schultz, C. "CLP(QS): A Declarative Spatial Reasoning Framework". In: Proceedings of the 10th international conference on Spatial information theory. COSIT'11. Belfast, ME, USA, 2011.

BIPS Co. (2015). BIM survey. Retrieved from https://bips.dk/files/news_files/bim_survey_2014_r0.pdf

BIMForum (2019). Level of Development (LOD) Specification. Retrieved from https://bimforum.org/lod/

Boeri, A., Antonin, E., Gaspari, J., & Longo, D. (2014). Energy Design Strategies for Retrofitting: Methodology, Technologies, Renovation Options and Applications. Southampton: WIT Press.

Danish Building Research Institute (2017), 'Be18'. Retrieved from https://be18.sbi.dk/be/.

Danish Energy Agency (2017). ‘Energimærkning af huse’, Energimærkning boliger. Retrieved from https://sparenergi.dk/forbruger/boligen/energimaerkning-boliger/huse.

Dansk Standard (2007). DS/EN 15251 Input Parameters for Design and Assessment of Energy Performance of Buildings -- Addressing Indoor air Quality, Thermal Environment, Lighting and Acoustics. Retrieved from https://webshop.ds.dk/en-gb/standard/ds-en-152512007

Dansk Standard (2006). DS/EN ISO 7730 Ergonomi inden for termisk miljø – Analytisk bestemmelse og fortolkning af termisk komfort ved beregning af PMV- og PPD-indekser og lokale termisk komfortkriterier.

Dansk Standard (2013). DS 447 Ventilation i bygninger - Makaniske, naturlige og hybride ventilationssystemerDeursch, R. (2011). BIM and Integrated Design. Hoboken: Wiley & Sons.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). BIM Handbook: A Guide to Building Information Modeling for Owners Managers Designers Engineers and Contractors. Hoboken: Wiley & Sons.

EU [European Union] (2016). Boosting Building Renovation: What potential and value for Europe? Retrieved from www.europarl.europa.eu/RegData/etudes/STUD/.../IPOL_STU(2016)587326_EN.pdf.

Gebser, M., Kaminski, R., Kaufmann, B., Ostrowski, M., Schaub, T., & Wanko, P. (2016). Theory solving made easy with clingo 5. in OASIcs-OpenAccess Series, Informatics 52, Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik.

Jalaei, F., Jrade, A., & Nassiri, M. (2015). Integrating Decision Support System (DSS) and Building Information Modeling (BIM) to Optimize the Selection of Sustainable Building Components. Journal of Information Technology in Construction, Vol. 20, No. 25, 399–420.

Jensen, P.A., & Maslesa, E. (2015). Value based building renovation – A tool for decision making and evaluation. Building and Environment, Vol. 92, 1-9. doi:10.1016/j.buildenv.2015.04.008

Kamari, A., Jensen, S.R., Corrao, R., & Kirkegaard, P.H. (2017a). Towards a Holistic Methodology in Sustainable Retrofitting: Theory, Implementation and Application. WSBE 2017 (World Sustainable Built Environment) conference, Hong Kong, China, 702-708.

Kamari, A., Corrao, R., & Kirkegaard, P.H. (2017b). Sustainability focused Decision-making in Building Renovation. International Journal of Sustainable Built Environment. Vol. 6, No. 2, 330-350. doi:10.1016/j.ijsbe.2017.05.001

Kamari, A., Jensen, S., Christensen, M.L., Petersen, S., & Kirkegaard, P.H. (2018a). A Hybrid Decision Support System (DSS) for Generation of Holistic Renovation Scenarios—Case of Energy Consumption, Investment Cost, and Thermal Indoor Comfort. Sustainability. Vol. 10, No. 4, 1255. doi:10.3390/su10041255

Kamari, A., Laustsen, C., Petersen, S., & Kirkegaard, P.H. (2018b). A BIM-based decision support system for the evaluation of holistic renovation scenarios. Journal of Information Technology in Construction, Vol. 23, No. 1, 354-380. doi:http://www.itcon.org/2018/18

Kamari, A., Corrao, R., Petersen, S., & Kirkegaard, P.H. (2018c). Tectonic Sustainable Building Design for the development of renovation scenarios – Analysis of ten European renovation research projects. SER4SE 2018 (seismic and Energy Renovation for Sustainable Cities) conference, Catania, Italy, 645-656.

Kamari, A., Schultz, C., & Kirkegaard, P.H. (2018d). NovaDM: Towards a formal, unified Renovation Domain Model for the generation of holistic renovation scenarios. ECPPM 2018 (12th European Conference on Product & Process Modelling) conference, Copenhagen, Denmark, 197-205.

Kamari, A., Jensen, S.R., Corrao, R., & Kirkegaard, P.H. (2019a). A Holistic Multi-methodology for Sustainable Renovation. International Journal of Strategic Property Management, Vol. 23, No. 1, 50-64. doi:10.3846/ijspm.2019.6375

Kamari, A., Schultz, C., & Kirkegaard, P.H. (2019b). Unleashing the diversity of conceptual building renovation design: Integrating high-fidelity simulation with rapid constraint-based scenario generation. SimAUD 2019 (10th annual Symposium on Simulation for Architecture and Urban Design) conference, Atlanta, USA, 29-36.

Kamari, A., Schultz, C., & Kirkegaard, P.H. (2019c). Constraint-based renovation design support through the renovation domain model. Automation in Construction. Vol. 104, 265-280. doi:10.1016/j.autcon.2019.04.023

Kim, J.I., Kim, J., Fischer, M., & Orr, R. (2015). BIM-based decision-support method for master planning of sustainable large-scale developments. Automation in Construction, Vol. 58, 95–108.

Kondyli, V., Schultz, C. & Bhatt, M. "Evidence-Based Parametric Design: Computationally Generated Spatial Morphologies Satisfying Behavioural-Based Design Constraints". In: 13th International Conference on Spatial Information Theory, COSIT 2017, 2017.

Molio (2016). Molio Price data. Retrieved from https://molio.dk/molio-prisdata/prisdata-footer/brug-m

Nielsen, A.N., Jensen, R.L., Larsen, T.S., & Nissen, S.B. (2016). Early stage decision support for sustainable building renovation: A review. Building and Environment, Vol. 103, 165–181. doi:10.1016/j.buildenv.2016.04.009

Norback, D., Lampa, E., & Engvall, K. (2014). Asthma, Allergy and Eczema among Adults in Multifamily Houses in Stockholm (3-HEStudy) - Associations with Building Characteristics, Home Environment and Energy Use for Heating. PLoS ONE, Vol. 9, No. 12. doi:10.1371/journal.pone.0112960

Rice, P. (1996). An Engineer Imagines. London: Ellipsis.

Schlueter, A., & Thesseling, F. (2009). Building Information Model Based Energy/Exergy Performance Assessment in Early Design Stages. Automation in Construction, Vol. 18, No. 2, 153–163.

Schultz, C., Bhatt, M., & Borrmann, A. "Bridging qualitative spatial constraints and feature-based parametric modelling: Expressing visibility and movement constraints". In: Advanced Engineering Informatics 31 (2017), pp. 2–17.

TABULA (2015). Typology Approach for Building Stock Energy Assessment. Retrieved from http://episcope.eu/building-typology.

TECNALIA (2015). Intervention criteria & packaged solutions for buildings renovation towards a NZEBR. Retrieved from http://www.nezer-project.eu/download/18.343dc99d14e8bb0f58bb3b/1440579936965/NeZeR_D2_3_NZEBR%20criteria.pdf.

VELUX (2016). Architecture for Wellbeing & Health | The Daylight Site pp 1–19. Retrieved from http://thedaylightsite.com/architecture-for-well-being-andhealth/

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. Automation in Construction, Vol. 38, 109–127. doi:10.1016/j.autcon.2013.10.023

Walega, P., Schultz, C. & Bhatt, M."Non-monotonic spatial reasoning with Answer Set Programming Modulo Theories". In: Theory and Practice of Logic Programming 17.2 (2017), pp. 205–225.

Xu, H., Huang, Q., & Zhang, Q. (2018). A study and application of the degree of satisfaction with indoor environmental quality involving a building space factor. Building and Environment, Vol. 143, 227-239. doi:10.1016/j.buildenv.2018.07.007.

Understanding the complexities of managing historic buildings through heritage BIM: a case study of Durham Cathedral

Kenneth Kelly[1*], James Charlton[1] and David Greenwood[1]
[1]Northumbria University
* email: Kenneth.kelly@northumbria.ac.uk

Abstract

The adoption of Building Information Modelling (BIM) in the management of built heritage is an exciting prospect, but one that presents some unknowns and complexities additional to those of modern buildings. If challenges can be identified and overcome, the adoption of Historic Building Information Modelling (HBIM), could offer a number of advantages, including: more efficient and effective archiving, monitoring, inspection and surveying of sites; better evaluation of conditions and historical development; and more informed procurement, estimating and scheduling of interventions, particularly those that are outsourced. HBIM offers a new approach of visualising and managing historic building and estates by offering efficiency and effectiveness in the conservation, long-term management and presentation of historic built assets. The key factors are (1) the ‘parametric’ and ‘intelligent’ potential of BIM; (2) the capacity of BIM to embed non-geometric information (specifications, material properties, reports, etc. along with unique theoretical and heritage information associated with heritage buildings); and (3) the accessibility and flexibility to access and utilise the data, both graphical and non-graphical. However, despite this potential, and growth in interest, there has, to date, been little research into what Maxwell’s (2014) COTAC BIM4Conservation report highlights as ‘a specific HBIM approach that is coherent and relevant, whilst also taking fully into account the wide diversity of issues that affect the heritage’. It is from this challenge, that the research discussed in this paper aims to contribute. Using Durham Cathedral as a case study, this paper presents an overview of BIM-based workflow processes and technologies applied to improve the way this UNESCO world heritage site is managed. The paper sets out the challenges and complexities in managing the estate and provides an insight into the approach taken to capture and visualise a HBIM solution that provides functionalities that improves efficiencies compared with traditional pre-BIM workflows. In doing so, the research provides an underpinning narrative for understanding the potential advantages, disadvantages, challenges and drivers of HBIM adoption for facilities management across the heritage sector. The paper draws conclusions and areas of future research that identify the need for a stronger understanding of the culture within heritage building for managing historic assets, and identification of Heritage Information Requirements (HIR) and the unique theoretical and heritage information associated with heritage buildings, in order to deliver a coherent and relevant HBIM approach.

Keywords: HBIM, BIM, Facilities Management, Historic England, Durham Cathedral

1. Introduction

Heritage buildings are unique in their characteristics and are more than just physical entities. They hold universal value to all humanity and have a legacy for generations to come. They promise to have forms, assets and systems that have been crafted and installed over centuries of modifications, repairs and developments. As a result, heritage buildings can offer complexities both in their form and the information they retain. How to record, organize and manage these complexities is a constant struggle for the parties that manage heritage buildings. However, tools, processes and approaches promoted by Building Information Modelling (BIM) could potentially provide a solution (Maxwell, 2014). The last decade has seen an increasing use of BIM within the Architectural, Engineering and Construction (AEC) industry. Primarily focused on the design and construction processes for new builds, the co-ordination, centralizing and visualization of information has also been applied to facility management processes to existing and heritage buildings. It is within this context, the use of BIM as a solution for managing heritage buildings where this paper is focused. The adoption of BIM in the management of built heritage is an exciting prospect, but one that presents some unknowns and complexities additional to those of a traditional or modern building. However, despite this potential, and growth in interest, there has, to date, been little research into what the Maxwell's (2014) COTAC BIM4Conservation report highlights as 'a specific HBIM approach that is coherent and relevant, whilst also taking fully into account the wide diversity of issues that affect the heritage'. It is from this challenge, that the research discussed in this paper aims to contribute. Using Durham Cathedral as a case study, this paper presents an overview of BIM-based workflow processes and technologies applied to improve the way this UNESCO world heritage site is managed. The paper sets out the challenges and complexities in managing the estate, and provides an insight into the development of a HBIM solution that provides functionalities that improves efficiencies compared with traditional pre-BIM workflows.

2. BIM and managing heritage buildings

BIM, as a term, can refer to both a model (i.e. a geometrical representation of an asset or a project with information attached) or the process of "creating and managing information on a construction project across the project lifecycle" (NBS, 2017a). It is the former application that is of interest in the current context and its potential within the context of historic buildings. The use of BIM on existing buildings within this context, is focused on creating an information rich 'intelligent' model to support the operation phase of building. This version of a BIM is referred to in BSI (2014) PAS 1192-3 document as an Asset information Model (AIM), a "single source of validated and approved information that relates to a built asset and is used during the operational phase of a building" (NBS, 2017b). The information comes in the form of both geometric and non-geometric data (parameters, reports, documents, etc.), with the geometrical data acting as a visual portal for the attached non-geometric data.

Within the context of Facilities Management (FM), a structured AIM can offer advantages over traditional approaches including: more efficient and effective archiving, monitoring, inspection and surveying of sites; better evaluation of conditions and historical development; and more informed procurement, estimating and scheduling of interventions, particularly those that are outsourced. Within the current culture of heritage building, information (2D plans, elevations and drawings, photographs, reports, operation and maintenance manuals, etc.) can be fragmented and not consistent. This can lead to inefficacies in how the data is used, and in the resulting outcome. The operational phase requires comprehensive set of well-structured information regarding the building asset (Nical & Wodyński, 2016). The adoption of an AIM allows for a central source of operation data to be created and structured, acting as a visual and accessible digital record for a project and its assets. Non-graphical information held within an AIM for modern buildings would typically relate to the operational information of an asset and may include the: manufacture; material; cost and performance rating, it's geometrical parameters, ID and location, related optional and maintenance manuals and reports, etc. Although relevant to the operation of a heritage building, a heritage AIM offers the opportunity to also include theoretical and heritage information: research material, photographs and scanned documents (Pauwels, Verstraeten, De Meyer, & Van Campenhout, 2008) relating to the use and development of the building over its existence. In doing so, a heritage AIM has the potential to not just be valuable to the operation of complex and unique heritage assets, but to also act as a structured historical record. It offers a new approach of visualising and managing historic and operational information for heritage buildings and estates, by offering efficiency and effectiveness in the conservation, long-term management and presentation of historic built assets. The key factors are (1) the ‘parametric’ and ‘intelligent’ potential of BIM; (2) the capacity of BIM to embed non-geometric information (specifications, material properties, reports, etc. along with unique theoretical and heritage information associated with heritage buildings); and (3) the accessibility and flexibility to access and utilise graphical and non-graphical data

3. Durham Cathedral

Durham Cathedral has dominated the City’s landscape for almost 1000 years. Constructed over 40 years from 1093 to 1133, the cathedral stands today as the “largest and finest example of Norman architecture in England" (UNESCO, 2012), and was inscribed on the World Heritage List by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1986, to recognise its architectural and historic importance (UNESCO, n.d.). Furthermore, the cathedral is designated a Scheduled Ancient Monument and Grade 1 listed property, giving it the highest legal protection for the built environment.

Based on the typical plan of a Latin cross (figure 1), centred on the four substantial piers of the crossing, the cathedral today has been adapted, modified and refurbished over the centuries. The earliest most notable additions were the Galilee Chapel in 1170-1175 and the 13th century central tower. In the late 17th century, the cathedrals bishop, Bishop John Cosin (1660-72), embarked on the first major restoration and refurbishment of the cathedral. Post Cosin the next major rework of the cathedral took place from 1777, that saw a period of significant works that were to alter the physical character by what would today be considered at best bad conservation practice, when architect George Nicholson smoothed off much of the outer stonework face (Stranks, 1970). In parts as much as 75mm were lost, that not only altered the appearance but substantially shorthand the life span of the materials leaving a legacy of replacement for future custodians. Further restoration took place in 1858 of the cloisters by Anthony Salvin and of the cathedrals central tower in 1859-60 by the George Gilbert Scott. Conservation projects have continued into the 20th and 21st century, with the 1930’s seeing the beginning of the restoration of St Cuthbert shrine to something that was to be more befitting to the pilgrimage and worship this was attracting, and more recently in 2017 work was undertaken to repair the central tower (The Chapter of Durham, 2019a). Conservation work is also planned for the central cloister in 2020, as part of a further 15-year repair and maintenance plan for the Cathedral and Precinct and develop appropriate opportunities to improve public access (The Chapter of Durham, 2019b).

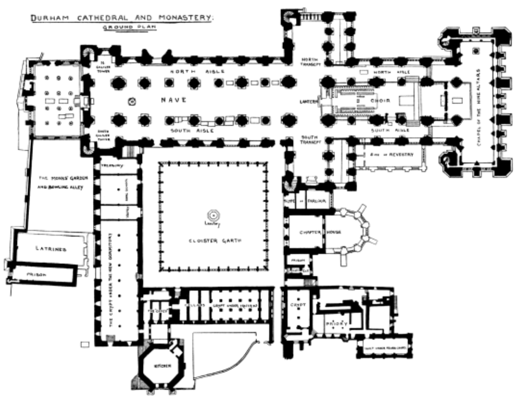


Figure 1: Durham Cathedral Plan (Bygate, 1900)

Throughout the adaption, modification and refurbishment over the centuries, the cathedral has been in constant use. Originally built as a monastic cathedral, it has long been a place of worship and pilgrimage, commemoration and culture; a place and a source of spirituality and inspiration. It has served political and military function being the seat of power for the Prince-Bishops and in 1650 saw the cathedral being used by Oliver Cromwell as a temporary prison holding around 3000 Scottish prisoners captured during the Dunbar (Durham World Heritage, n.d.). In more recent times the cathedral has been used as a movie and TV backdrop and been a centre piece of cultural arts and exhibition. This along with the World Heritage status has brought a new demographic of visitor, that has seen the addition of and improvement to public facilities including restaurant, toilets and retail shopping. Today the cathedral attracts approximately 700,000 visitor's pa, whilst still being used for daily services, which brings with it its own set of logistical challenges and adds to weekly running costs of £60,000 per week and the requirement of continual maintenance (Durham World Heritage, n.d.).

The picture is clear, the cathedral is a complex, unique and highly protected building, with layers of history imbedded in its structure, a collection of unique assets, a variation of uses by a range of different users, a constant program of maintenance and repair and a high running costs. Efficiencies need to be made to help manage and maintain the cathedral for future generations and to ensure limited budgets support the immediate and long-term running of this culturally and spiritually significant building.

4. A BIM solution for managing Durham Cathedral

Previously, the FM team at Durham Cathedral placed their reliance on architectural and sometimes artistic drawings from the late 20th century as a base for their decision making and assessment of condition of the fabric of the building. Their ability to maximize the use of the drawings to support operational processes was further hindered by their accessibility (often held offsite) and the fact that they were frequently misplaced, unorganised and inaccurate. There is no searchable way of accessing the information and there is a lack of indexing on the information that currently exists (Tapponi, Kassem, Kelly, Dawood, & White, 2015). This lack of accuracy and accessibility to the drawing material and supporting information has resulted in inefficient processes and increased costs to projects, with architects and contractors having to be paid to make bespoke studies per project, potentially duplicating effort, adding to the time and cost of a project. Furthermore, due to the lack of information about the structure's build-up, unless intrusive surveying was undertaken, it was difficult to determine typical measurements (thickness and volume) that are needed for the restoration process (Tapponi et al., 2015).

To investigate the potential of a BIM solution for heritage buildings, the Chapter House at Durham Cathedral was chosen. This project aimed to capture and model the historic structure to create a 3D digital model to support the improved management of the world heritage building. In doing so, the project aimed to gained an understanding on the potential advantages, disadvantages, challenges and drivers of HBIM adoption for facilities management across the heritage sector.

4.1 Scan to BIM

In undertaking a BIM solution for Durham Cathedral, the first stage required the need to identify a source of base data that could be used to support the modelling process. As existing drawings were deemed inaccurate, or were inaccessible, the team opted to utilize a laser scanning approach over traditional surveying techniques to create an up-to-date and accurate record of the cathedral. Accurate measured surveys have long been recognised as an important part of the renovation and redesign process and have a fundamental role in BIM of existing and heritage buildings. Laser scanning has proved to be a vital tool in the production of BIM surveys, and has key advantages over traditional surveying methods when being used to support BIM processes. BIM requires a much higher level of detail in the survey and most importantly it requires this in 3D (Historic England, 2017).

With an original focus on helping to capture and create accurate As-Built models of complex oil rigs and plant facilities, the last decade has seen an increasing application of laser scanning technology being applied within the wider architectural sector, as the technology becomes more affordable, accessible and portable. Today there are a range of scanners, designed to fit different demands, purposes and preferences of the user. Although specifications can differ most laser scanners follow the same principal. A laser scanner emits a pulsing or continuous laser beam from the scanning unit, towards the area being scanned. The laser bounces back when it hits a surface and the position (distance from the scanner) of that event is recorded based on the time of flight or the phase shift of the laser (Arslan & Kalkan, 2013) and the corresponding horizontal and vertical angels of the rotating laser. The process is repeated upwards of a million points a second, as the scanner sweeps horizontally and vertically over the surrounding area (Tapponi et al., 2015). As the process is based on line of sight from the unit, there may be a need to carry out more scans if the area to be scanned is greater than the unit's range, or if parts of the environment are obstructed by other elements. At each scan position, certain scanners can use built-in or external cameras to capture photographs to add colour to the survey data. This can be very useful when using the data to create BIM to help distinguish architectural features and material changes. The result of a typical laser scanning process is a collection of individual scans or point clouds of the area surveyed. To create a single representation of the entire scene, each individual scan can be registered with the others to create a single point cloud. Some modern scanners can do this on site during the scanning process, while others require an additional post-processing and registration process. The latter can be supported by using scan targets, which when located in each scan, are identifiable and linked together in the supporting software and by ensuring sufficient overlap of captured data between scans.

Within this pilot study the team used a FARO Focus^{3D} S 120. This survey-grade 3D terrestrial laser scanner is a phase-based panoramic-type scanner equipped with a built-in tilt sensor, barometer, and magnetic compass. The scanner has the ability to accurately capture up to 305^{O} of an environment, at a range from 0.6m – 120m, up to 976,000 points per second, with a single survey point every 3.8mm, and to an accuracy of +/- 2mm from a 25m range (FARO, 2013). Over the course of two days, the team completed 42 scans to captured external and internal features of the chapter house. The result was a 250-million-point highly accurate point cloud of the site as well as a record of the intricate detail of the site's current condition (Figure 2). However, although very accurate and detailed, the resulting file size (8 gigabyte) was too large for efficient use within BIM based software. A key point for a scan to BIM process is to provide point clouds in both a file format and size that allows for efficient modelling work. The team opted to export the data as a e57 file, selected only the data required for modelling and exported at a density of 10%. The resulting file was significantly smaller in file size but retained more than enough points (10 million) to allow for efficient modelling to take place.

Figure 2: Example of captured laser scan data of Durham Cathedral

4.2 Model creation

The process of creating the BIM of the chapter house was carried out using Revit. This required for the point cloud data to first be imported into Autodesk Recap to create a compatible format, as there is no direct file link between the FARO software and Revit. Once imported into Revit, a variation of modelling approaches was taken to "trace over" the architectural features within the point cloud to create the final BIM (Figure 3). Due to the unique nature and high architectural detail of the historic features within the chapter house, it was not possible to use standard modelling tools (system families). Instead, the Generic Model tool was used, allowing the creation of bespoke components that were more closer in detail to real architectural features, and then manually adding any object-specific parameters to it (Kelly, 2018). Even though this approach allowed for a more accurate model to be created, limitations in Revit did restrict the modelling approach, creating inaccuracies in the final model. One such error can be found in the southern wall, that was shown in the point cloud to lean out by 300mm from the vertical at the highest point of the wall. In consultation with the estates team at Durham Cathedral, it was decided to straighten this wall vertically within the BIM, to add a note to the wall highlighting the discrepancy and to provide the estates team with the point cloud to support any measurement processes. After the geometrical model was complete, a process was undertaken to populate the model with provided non-geometrical information (reports, condition classifications, comments, etc.) and parametric data, creating a data-rich ‘intelligent’ AIM of the chapter house.

Figure 3: Point cloud data of Chapter House, Durham Cathedral and resulting BIM.

The creation of the AIM of the chapter house provided the estates team with an up-to-date, structured and accessible model from which traditional outputs such as elevations, sections and floor plans could be accessed, along with any attached non-geometrical information. The model also allowed the creation of condition surveys to interlink with the history of each element; maintenance schedules; accurate stone surveying; visual walkthroughs for virtual tours; scaffolding simulation for refurbishment planning; scenario planning (planning an exhibition inside a room); with field tools that utilise mobile technology being available to explore and update the model on site (Kelly, 2018) (Figure 4). One further advantage resulting from undertaking a BIM approach related to the identification of wall and ceiling thicknesses and volumes. The completed laser scanning survey captured the faces of the architectural elements. When the resulting void was modelled as solid geometry within Revit, it was possible to measure the thickness at any point and calculate the volume of any part of the AIM. For the first time, the estates department were able to accurately determine the thicknesses of walls, and the volume of concrete used in the vaulted ceiling. Therefore, demonstrating the ability of the process to reduce the need to undertake expensive, time-consuming and potentially intrusive surveying.

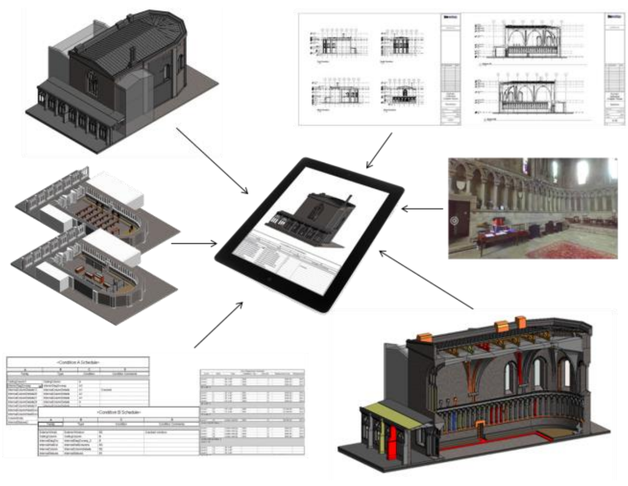


Figure 4: Resulting AIM and its features, running on a mobile device

5. Findings: Challenges and guidance

From undertaking the research, the team have been able to gain insight into the complexities of managing heritage buildings. It is clear that heritage buildings come with their own unique challenges, in relation to: the historical assets themselves; the accuracy and accessibility of current graphical and non-graphical information, and the processes and bureaucracy in place for managing historic buildings. However, it is through these challenges, where the opportunity of BIM can play a helping hand, although in doing so, it too presents new challenges. The undertaken project demonstrated the potential for BIM to improve efficiencies in managing heritage buildings, by offering an accessible platform that utilizes structured digital information and 3D models to deliver greater value. The resulting AIM creates a centralised point of access for information relating to the building and its historic assets. In comparison to modern buildings, this non-geometrical information can relate not only to operational information of an asset but could also include theoretical and heritage information relating to the use and development of the building over its existence. In doing so, a heritage AIM has the potential to not just be valuable to the operation of complex and unique heritage assets, but to also act as a structured historical record for preserving and maintaining information for future generations. However, the delivery of a heritage AIM creates some new challenges.

(1) **Level of detail.** The research has previously discussed the relationship between the architectural details of heritage buildings, the appropriateness of laser scanning in supporting data capture and BIM, and the capabilities of BIM tools to reproduce the geometrical detail. This process can be complicated depending on the complexities and detail of the historical features and assets and the needs of the client. Decisions will be required to establish a balance between geometrical accuracy, level of detail and the requirements of the model to support facilities management processes. Where accurate geometry cannot easily be created, supplementary data could be used. Within the case study presented, the team were able to provide the millimetre accurate point cloud and a virtual tour (a biproduct of the scanning process) alongside the AIM to help with measurements and visual reviews (at time of capture).

(2) **Access to information.** On completion of the geometrical model, the next stage in creating an AIM for heritage buildings would be to imbed the necessary non-geometrical information in a structured and useful way. For the pilot study, the team were provided with relevant information, however, one of the main drivers for the initial research was the lack of accessibility and poor structure of existing information. Correct BIM processes can support the structuring of the information, but a program of information identification and retrieval may be required to collate the required information and establish its capability to attach to the AIM.

(3) **Technical skills.** To be able to complete a base model that can carried forward, a combination of the adequate hardware, software and skillset is required to achieve the whole process from laser scanning to producing an 'intelligent' AIM. Although the initial process of data capture and BIM can be done using external subcontractors, there will be a need inhouse to utilise the model and keep the model up-to-date. As with any AIM, its value decreases if it is not kept up-to-date. On delivery of the model to Durham estates, it became apparent that all relevant team members who engage and support AIM would require a level of training and initial support in to how to utilise and update the model, in order to overcome any lack of technical knowledge.

(4) **Current culture and procedures**. The delivery of an AIM for the pilot study aimed to demonstrate and gain further insight into the capabilities of BIM in supporting FM processes for heritage buildings. It was clear from follow-on discussions with Durham estates, that a larger exercise was required to understand FM processes and how they can be aligned to a BIM workflow. Although the pilot study demonstrated that a wider implementation of a BIM workflow to support FM processes would have the benefit of reducing costs and increasing efficiencies and knowledge, the estates team were restricted by current processes and bureaucracy and allocated funding streams that were in place. Through the pilot study it was highlighted that current processes that generated the bespoke and then inaccessible drawings would be hard to step away from as they had been in place for decades. Furthermore, although there were funding streams in place to support the running and maintenance of the cathedral, all funds for several years to come had been already been allocated. Therefore, for Durham to escalate BIM adoption in the future, it was established that a further research was required to understand current FM processes, and a solid business case, based on the advantages from this pilot project and potential future applications, needed to be developed to demonstrate the efficiencies of a heritage AIM whilst justifying the improved upfront costs.

It is worth noting that the challenges identified for creating an AIM for heritage buildings are also relative for the creation of an AIM for any existing building. Authors have noted similar challenges in creating AIM for existing buildings (Kiviniemi & Codinhoto, 2014; Nical & Wodyński, 2016; Pishdad-Bozorgi, Gao, Eastman, & Self, 2018). One paper to note is Kassem, Kelly, Dawood, Serginson, & Lockley (2015) exploration of creating an AIM for a large university complex. Within the paper, the authors identify challenges in: workforce and process efficiencies; accuracy of records of geometrical information and implementation challenge and maintenance of models when creating an AIM for existing buildings. Although the titles of the challenges differ, the essence of the challenges are similar to those established from this study, with the author identifying organisational barriers, a lack of accurate and structured information and a need to agree LOD, as challenges to creating AIM for existing building. However, from the review of literature, it appears that although challenges are shared, the additional and bespoke complexities of heritage buildings amplify these challenges.

5.1 The need for a Heritage Information Requirements (HIR)

The challenges identified can be split into two distinct areas (1) information requirements (level of detail and access to information) and (2) current culture (technical skills and current culture and procedures). The latter is a significant barrier to implementing BIM workflows into heritage buildings, and one that needs further research before recommendations can be made. However, based on the research undertaken, it is possible to make recommendations in relation to supporting the challenges that fall within the area of information requirements. Current BIM processes for new developments follow three distinct stages (1) **understanding** the client's needs and project team's capabilities and (2) the **development** of a BIM to support collaborations, communication and coordination throughout the design and construction phases, and (3) **application** within construction and/or more increasingly to support facilities management purposes (Figure 5).

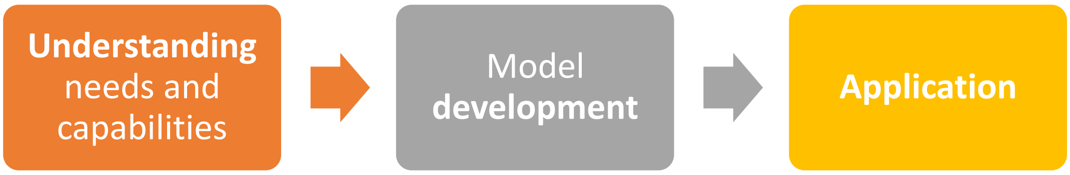


Figure 5: Simplified BIM Workflow

These three stages are similarly applicable to heritage buildings, however it is often the 2nd and 3rd stages that take focus. This study has demonstrated the technical capabilities and solution in creating an AIM for heritage buildings, but in doing so established the importance of the first stage in order to drive the project and get value out of the resulting AIM. Within the application of BIM on a modern development, the project would be driven by documentations such as Organisational Information Requirements (OIR), Asset Information Requirements (AIR) and the Employers Information Requirements (EIR). These key documents set out what is required from the BIM process and any resulting AIM. However, due to the complexities and uniqueness of historical assets, along with the potential for a heritage AIM to include theoretical and heritage information, these documents themselves may not deliver the supporting foundation for a HBIM process. Although further research is required, it can be proposed that for heritage buildings, in addition to the OIR, EIR, and AIR, there is a requirement for heritage organisation to create a Heritage Information Requirements (HIR) that details specific information requirements relating to the historic assets and the unique theoretical and heritage information associated with heritage buildings, to deliver a coherent and relevant HBIM approach.

6. Conclusions

The focus of this study has been to gain an insight into the potential application of BIM workflows in supporting facility management processes of heritage buildings. Through the application and reflection of a pilot study at Durham Cathedral the paper has aimed to provide a narrative on the creation of AIM for heritage buildings and identify challenges and provide guidance for those wishing to develop this initial research. From the research undertaken, it is clear that heritage buildings are complex and unique structures. Although the research focused only one case study, the extreme nature (processes, uses, scale and size, etc.) of the cathedral has been able to provide a valuable insight into the complexities that heritage buildings. It can be surmised that unlike modern buildings, for which BIM is comfortably applied, heritage buildings have unique architectural details, layers of history imbedded into their structure, a requirement for constant and complex programs of maintenance and repair and have high running cost. For such buildings, it is important that efficiencies in management, maintenance and repair and use are needed to help reduce costs and preserve the historical assets for future generations. The processes and ethos promoted by BIM has been shown within this paper to have a potential to support. Through a process of laser scanning and modelling, the team were able to deliver a working prototype of an AIM for heritage buildings. They were able to successfully demonstrate the capabilities of the model to present graphical views (plans, elevations, sections, etc.) on request and imbed and provide access to non-graphical data (specifications, material properties, reports, etc. along with unique theoretical and heritage information associated with heritage buildings). In doing so, showcase the potential of BIM to provide an accessible, accurate and visual database for supporting facility management processes. However, it was through this process that key challenges and areas of future research were identified. Although identified challenges are relative to creating AIM of existing buildings, the challenges are amplified by the bespoke complexities of heritage buildings. It was established that there is a need to further understand the culture in managing heritage buildings, to understand not only the technical capabilities, but the processes and bureaucracy in place for making decisions and implementing changes that have been created by their protected status. A greater understanding is needed to understand these processes and to establish how BIM can support. Another key challenge relates to the information requirements for heritage buildings. Due to the complexities and uniqueness of historical assets, along with the potential for a heritage AIM to include theoretical and heritage information, alongside operational information, it can be proposed that in creating an AIM for heritage buildings, in addition to the OIR, EIR, and AIR, there is a requirement for heritage organisations to create a Heritage Information Requirements (HIR) that details specific information requirements relating to the historic assets and the unique theoretical and heritage information associated with heritage buildings, to deliver a coherent and relevant HBIM approach.

References

Arslan, A., & Kalkan, K. (2013). *Comparison of working efficiency of terrestrial laser scanner in day and night conditions. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* (Vol. XL-7/W2). doi:10.5194/isprsarchives-XL-7-W2-19-2013

BSI. (2014). *PAS 1192-3: 2014: Specification for information management for the operational phase of assets using building information modelling*. Retrieved from https://shop.bsigroup.com/Sandpit/PAS-old-forms/PAS-1192-3/

Bygate, J. E. (1900). *The Cathedral Church of DURHAM by J. E. Bygate.* (Second). Edinburgh: The Riverside Press Limited. Retrieved from http://www.ajhw.co.uk/books/book350/book350a/book350a.html

Durham World Heritage. (n.d.). Durham Cathedral - Durham World Heritage Site. Retrieved 14 April 2019, from https://www.durhamworldheritagesite.com/architecture/cathedral

FARO. (2013). *A leap in innovation and efficiency to lower your costs*. Retrieved from www.faro.com/focus

Historic England. (2017). *BIM for Heritage Developing a Historic Building Information Model*. Retrieved from https://historicengland.org.uk/advice/technical-advice/recording-heritage/

Kassem, M., Kelly, G., Dawood, N., Serginson, M., & Lockley, S. (2015). BIM in facilities management applications: a case study of a large university complex. *Built Environment Project and Asset Management*, *5*(3), 261–277. doi:10.1108/BEPAM-02-2014-0011

Kelly, G. (2018). BIM Academy – Durham Cathedral | Case Studies | The BIM Hub. Retrieved 14 April 2019, from https://thebimhub.com/2018/02/13/case-study-durham-cathedral/#.XNs1fOhKjid

Kiviniemi, A., & Codinhoto, R. (2014). *Challenges in the Implementation of BIM for FM—Case Manchester Town Hall Complex*. In *Computing in Civil and Building Engineering (2014)* (pp. 665–672). Reston, VA: American Society of Civil Engineers. doi:10.1061/9780784413616.083

Maxwell, I. (2014). *Integrating Digital Technologies in Support of Historic Building Information Modelling: BIM4Conservation (HBIM)*. Retrieved from https://cotac.global/resources/COTAC-HBIM-Report-Final-A-21-April-2014-2-small.pdf

NBS. (2017a). What is BIM? | NBS. Retrieved 20 April 2019, from https://www.thenbs.com/knowledge/what-is-building-information-modelling-bim

NBS. (2017b). What is the Asset Information Model (AIM)? | NBS. Retrieved 20 April 2019, from https://www.thenbs.com/knowledge/what-is-the-asset-information-model-aim

Nical, A. K., & Wodyński, W. (2016). Enhancing Facility Management through BIM 6D. *Procedia Engineering*, *164*, 299–306. doi:10.1016/j.proeng.2016.11.623

Pauwels, P., Verstraeten, R., De Meyer, R., & Van Campenhout, J. (2008). *ARCHITECTURAL INFORMATION MODELLING FOR VIRTUAL HERITAGE APPLICATION*. In *International Conference on Virtual Systems and Multimedia (VSMM)*. Limassol, Cyprus. Retrieved from https://biblio.ugent.be/publication/434809/file/481646.pdf

Pishdad-Bozorgi, P., Gao, X., Eastman, C., & Self, A. P. (2018). Planning and developing facility management-enabled building information model (FM-enabled BIM). *Automation in Construction*. doi:10.1016/j.autcon.2017.12.004

Stranks, C. J. (1970). *Durham Cathedral.* Pitkins Pictorials.

Tapponi, O., Kassem, M., Kelly, G., Dawood, N., & White, B. (2015). *Renovation of Heritage Assets using BIM: a Case Study of the Durham Cathedral*. In *the 32nd CIB W78 Conference 2015*. Eindhoven, The Netherlands. Retrieved from http://itc.scix.net/data/works/att/w78-2015-paper-073.pdf

The Chapter of Durham. (2019a). Durham Cathedral. Retrieved 26 April 2019, from https://www.durhamcathedral.co.uk/news/durham-cathedral-central-tower-unwrapping

The Chapter of Durham. (2019b). Reports, plans and goals | Durham Cathedral. Retrieved 26 April 2019, from https://www.durhamcathedral.co.uk/about-us/reports-plans-goals

UNESCO. (n.d.). Durham Castle and Cathedral - UNESCO World Heritage Centre. Retrieved 29 March 2019, from https://whc.unesco.org/en/list/370

UNESCO. (2012). *Researching the Historic Urban Landscape The Challenges of the Secular, Religious and Historic Urban Environment*. Retrieved from https://whc.unesco.org/en/events/951/

BIM-adoption within Small and Medium Enterprises (SMEs): An existing BIM-gap in the building sector

Patryk Makowski[1], Aliakbar Kamari[1*] and Poul Henning Kirkegaard[1]
[1]Department of Engineering, Aarhus University
* email: ak@eng.au.dk

Abstract

The AECO[1] industry is fast going digital, with Building Information Modelling (BIM) becoming an essential part of it. BIM adoption is seeing an expanding trend as more and more building sector stakeholders can realize how by prototyping the building virtually to be built, they can review the design more efficiently, obtain more accuracy in construction and if need be, evaluate alternatives concerning cost and other parameters. In this regard, Small and Medium Enterprises (SMEs) form a significant part of the sector; thereby their innovative practices are crucial in performing BIM within an Integrated Design (ID) schema. Many governments support adoption of BIM-oriented ID approaches on their national markets, yet the involvement of small companies in the common BIM-adoption is considered inadequate. As such, a common BIM-gap exists and negatively impacts the overall pace of adopting innovative technologies in construction. Inspiring SMEs to adopt BIM can help the AECO industry including each individual firm enhancing their productivity as well as economic profit and reducing risks. The sooner small and medium companies decide to undertake BIM transformation and dumping the traditional construction process as the only right choice the better for all stakeholders. On the basis of this underlying hypothesis, the aim of the present research study is firstly to identify issues that are the cause for the BIM-gap to emerge and secondly to investigate what actions could be undertaken with an attempt to reduce it.

The research methodology used in this study consists the data collection from various experienced practitioners including Site Engineers, Construction Managers, Schedulers, Cost Estimators, BIM coordinators, Consultants, and Designers with an understanding of the on-site BIM implementation. In order to collect the appropriate amount of data in a timely manner that could serve further deduction, a mixed method called triangulation is used, including phone interviews; an extensive literature review; non-interactive interviews in the form of online forum discussions including an online survey and review of relevant practitioners' opinions. Data collection is then followed by an analysis of the collected data and the extraction of most relevant facts. This is the conclusion of this study that the costly BIM-adoption appears unappealing to many SMEs due to various obstacles containing lack of motivation and need to change, as well as the issue of many of the popular BIM platforms not being designed to suit the specific needs of SMEs.

Keywords: Building Information Modelling (BIM), BIM-adoption, Small and Medium Enterprises (SMEs), Integrated Design (ID).

[1] Architecture, Engineering, Construction, Operation

1. Introduction

The AECO industry is fast going digital, with Building Information Modelling (BIM) becoming an essential part of it. Krygiel et al. (2008) discuss BIM is an emerging methodology in the AECO industry since the intelligent digital three-dimensional model-based process of BIM can be used to plan, design, structure, manage, and analysis buildings. Succar (2009) states BIM is a set of technologies, processes, and policies enabling multiple stakeholders to design, construct and operate a facility collaboratively. This underlines three critical factors to BIM including people, process, and technologies. BIM (Eastman et al., 2011) has the potential to aid designers to provide the required geometrical and analytical data of an existing building 3D model to select and evaluate the proper type of design alternatives during the early design stage (Kamari et al., 2018a; Kamari et al. 2018b) and to make decisions that have a significant impact on the life cycle of the building projects.

BIM technology allows Integrated Design - ID to flourish, encourages - and provides a vessel and conduit for - the sharing of information between the design and construction team (Deursch, 2011). As such, BIM enables Integrated Design – ID and therefore makes it possible. ID through BIM can be understood as a collaborative method for designing buildings that emphasizes the development of a holistic design (Kamari et al., 2018c). It strives to be holistic in that it involves stakeholders (architects, engineers, contractors, and clients) from the earliest stages, each having input into what goes into making the decisions that will lead to the completed project. It, therefore, strives to take every team member's point of view into consideration, and it is holistic in that these decisions are made with all the information shared at one time, up front and not in the more traditional linear fashion, each entity maintaining and controlling the distribution of its own locus of information (adopted from Deursch, 2011). ID and BIM are seeing as expanding trends as more and more building sector stakeholders can realize how by prototyping the building virtually to be built, they can review the design more efficiently, obtain more accuracy in construction and evaluate alternatives concerning cost and other parameters.

1.1 BIM-adoption around the world

Figure 1 illustrates the result of a study that was carried out by RIBA Enterprises (NBS, 2016) concerning the awareness and adoption of BIM within the international design community. It demonstrates that the awareness of BIM throughout the sector is nearly above 90% for the four out of five surveyed countries.

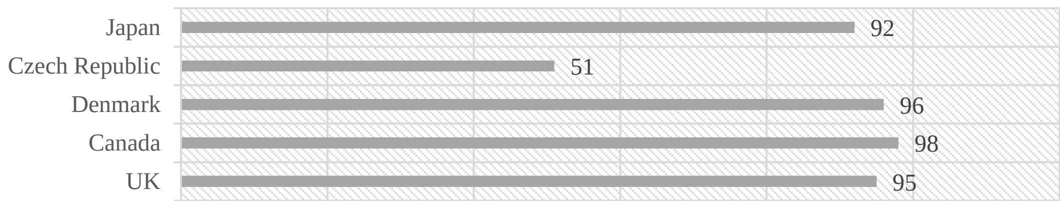


Figure 1: BIM-adoption (adapted from NBS, 2016)

In this survey, BIM awareness and adoption are highest in Canada and Denmark, and lowest in the Czech Republic. Both Canada and Denmark are reported a majority using BIM on at least some projects in the previous year. In Japan and the UK, the figure is just under half. It is noticed that BIM is increasingly becoming the norm for construction information across a range of countries and adopting BIM may become a prerequisite for working overseas. Even though the level of adoption of the technology is raising every year, as the outcome of the second survey by RIBA Enterprises (NBS, 2018), it is observed that there is still more than one-fourth of UK companies that do not utilize BIM technologies.

It is worth considering why such a large number of companies does not decide to make this transformation together with how BIM-adoption of the market can be improved (Hosseini, 2016; Forsythe, 2014). Distinguishing the BIM non-users with regards to practice size (small practice - 15 staff members or less, medium – 16 to 50 and large – more than 50) exposes a tendency, which small companies are more resistant in the implementation of BIM processes in their practice (as demonstrated in Figure 2) than their more substantial equivalents. Ghaffarianhoseini et al. (2016) based on their research on investigating the BIM readiness and implementation strategy for SMEs (Small or Medium Enterprises) in the UK, argue that almost 75% of UK's SMEs had yet to start their BIM journey in 2016.

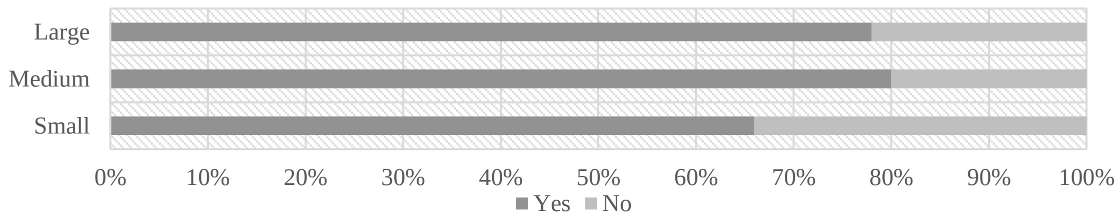


Figure 2: BIM adopted regarding the scale of the project (adapted from NBS, 2018)

1.2 Revealing a BIM-gap in terms of adoption

The BIM-gap refers to a growing digital division between BIM-adopters and non-adopters in the construction sector. BIM-related technologies are very rarely integrated across all phases of a project and its involved stakeholders, and thus the potential is not fully obtained (Dainty et al., 2017, Hosseini, 2016). Since the adoption of BIM occurs with facing specific challenges (i.e. financial aspects), larger companies are often better equipped to overcome them. As a result, those with the most resources begin adopting, training and learning skills and ultimately take advantage of the opportunities that i.e. BIM can bring into a company. These companies adopt earlier and gain more from adopting BIM technology, which leads to increasing inequalities in the market (Dainty et al., 2017; Forsythe, 2014). Poirier (2015b) states that there is also an insufficient or disproportionately low representation on BIM implementation for the SMEs in the relevant research findings, which tend to generalize and decontextualize real practices in the AECO industry. Since BIM-adoption requires collaboration and handing the model from the design team through the entire supply chain, according to Forsythe's (2014) analysis of BIM-adoption in Australia, small contracting enterprises are the most reluctant towards BIM technologies and constitute the weakest link in BIM-based supply chains. The differences of attitude towards BIM-adoption varies not only depending on the size of the company but also on its role played in the construction process and corresponding responsibilities.

It is noticeable that the use of BIM across SMEs varies among architects, engineers, general contractors and subcontractors (Forsythe, 2014). Small architectural and consultancy companies are more likely to equip themselves with Information and Communication Technology (ICT) that allows adapting to a new digital design practice (Forsythe, 2014). This brings up the question about who should deal with the managing and developing BIM technologies in the SMEs? Considering that BIM manager's role differs substantially from the traditional construction manager's role and the fact that small practices are limited with their access to resources, hiring a person responsible solely for BIM management turns out to be simply too expensive. However, Klaschka's case study of Poulter Architect's practice (2014) demonstrates that in the small-scale projects it is possible to combine traditional and BIM-related roles. The authors continue, the interviewed owner of the company declares that "the smaller scale of the projects I work on means that I can combine the roles of architect, lead consultant, and BIM manager. It also offers the potential to provide further services such as environmental analysis and materials scheduling". This implies how different the SMEs' project environment is compared to the large corporations.

Size of a construction company determines contexts and pressures facing it, hence the BIM-gap in the sector. A literature review carried out by Lu et al. (2008) discusses SMEs' different challenges in BIM transformation with reference to the role of the owner(s)/manager(s), company structure, resource limitations, and family ownership which form a specific business environment. However, the lesser scale of projects means that a company has this "safety net" of possibility to easily reverse out of early projects into CAD, in case of overwhelming difficulties (Klaschka, 2014). It creates an environment that is not strictly more challenging but presenting different challenges than in larger scale construction and those different challenges require a different approach.

Currently, there are many new advanced technologies being presented to the sector by software companies, and there are also many analyses being undertaken to get a better insight on how the sector is changing and is expected to change in the future due to general BIM implementation. Some research study focuses on criticizing the imperfections of BIM and suggests that higher resolution and more practically oriented approaches are needed for enhancing BIM implementation (Miettinen & Paavola, 2014). However, targeting and empowering the weakest link in an Integrated Design – ID framework (which concerns SMEs), as well as the BIM-gap phenomenon, is far from being popular investigated research problems (Forsythe, 2014). Every company's goal is to be competitive on the market and producing revenue, but since BIM-adoption in the SMEs is lower (unless an external intervention would kick), beginning a more extensive BIM implementation for SMEs will remain more resistant to the application of ICT. Therefore, they pursue with conventional construction processes for a longer period, and it leads to slowing down the sector's growth and BIM-adoption. In this perspective, the aim of the present research study is firstly to identify issues that cause the existing BIM-gap to emerge and secondly to investigate what actions can be undertaken with an attempt to reduce them towards enhancing BIM-adoption for the SMEs. The intention is to provide these companies with potential solutions that can enhance their productivity and reduce risks via the utilization of BIM-related technologies. The paper is structured with section 2, which summarizes the methodology for developing the results, whilst section 3 gives further detail of the analysis. Section 4 discusses the results, and finally, section 5 presents the conclusion and further research work.

2. Methodology

The methodology utilized in this research includes mixing of quantitative and qualitative research methods. It denotes a comprehensive data collection from various sources such as literature review, practitioners, websites, and through conducting online forum interviews to integrate different types of data and so more reliable interpretation of the results. In order to assure the trustworthiness of findings, the triangulation mixed method is used (Groat et al., 2002). As such, different types of data sources are utilized in order to offset the weaknesses.

What makes up for a significant part of this research is literature reviews focusing on BIM-adoption and implementation. In addition, the research methodology comprises the data collection from various experienced practitioners including Site Engineers, Construction Managers, Schedulers, Cost Estimators, BIM coordinators, Consultants, and Designers with an understanding of the on-site BIM implementation. The results are then categorized and analyzed in the form of a histogram through gathering the information about common covered issues in the literature. The categories are selected considering the coverage of the identified challenges in the literature with at least one or more of the relevant investigating barrios. Moreover, research involves a number of interactive interviews in the form of online forum discussions including an online survey, querying issues concerning adopting BIM in their practices as well as a review of relevant practitioners' opinions that found on the internet relevant to the same topic. This allows us to reach out to a wide range of practitioners around the globe (Poland, USA, Colombia), which contributes to the findings' universal character.

3. Analysis

Following the reviewed literature and the performed analysis, many of the sources present similar findings which can be categorized in specific categories including *motivation, knowledge, cooperation, software, skills,* and *costs*. Hereafter, the established parameters were verified through a consensus-based approach. In doing so, based on the specific challenges covered in each of the reviewed papers as well as the relevant introduced parameters, a subjective assessment scale (from 0 to 5, where 0 stands for "not mentioned" and 5 for "crucial") of the problems was undertaken (see *Table 1*). This helps us to structure an overview of the character and scope of the issues within BIM-adoption being faced by the SMEs, which subsequently contributes to the identification of what actions might bring improvement in the existing situation.

Table 1: Identification and evaluation of the challenges in BIM-adoption for SMEs

	Davies et al., 2017	Bargstädt, 2015	Migilinskas et al., 2013	Mäki & Kerosuo, 2015	Malacarne et al., 2018	Azhar, 2011	Miettinen & Paavola, 2014	Poirier et al., 2015a	Poirier et al., 2015b	Arayici et al., 2011	Dainty et al., 2017	Forsythe, 2014	Sebastian et al., 2009	∑
Motivation	4	0	4	0	0	0	4	4	5	4	4	4	2	35
Knowledge	3	0	2	0	1	2	3	2	3	3	4	1	2	26
Cooperation	3	0	5	4	2	5	3	2	3	3	0	4	0	34
Software	2	2	4	2	4	0	0	0	0	1	2	0	3	20
Skills	4	3	3	4	2	2	1	0	3	4	3	4	0	33
Costs	0	1	4	0	4	0	0	0	3	1	2	3	0	18

In the following, we use the identified categories (or lenses) in order to investigate adoption and implementation barriers.

Motivation - Even though the phenomenon of "the BIM hype" – a blind belief in future-oriented visions of the BIM's advantages (aka the "BIM utopia") – can be noticed throughout the AECO sector (Miettinen & Paavola, 2014). SMEs are characterized by a tendency of skepticism towards implementing this innovation (Dainty et al., 2017). Leaders of SMEs are often scared of implementing BIM due to that the evidence of positive Return on Investment (ROI) ratio is very difficult to obtain (Poirier et al., 2015a) and are also aware of risks that come with disruptive and radical innovation such as ROI.

Knowledge - Many of the listed challenges have a common denominator as misunderstandings, improper perceptions, lack of experience, topics that are insufficiently represented in research findings when it comes to BIM (Arayici et al., 2011; Dainty et al., 2017; Davies et al., 2017; Miettinen & Paavola, 2014).

Cooperation - Since BIM is an element of an ID schema, the mindset of trust and transparency and the principle of effective and open communication are also relevant in the BIM implementation process. Many companies struggle with changing their cooperation practices from the traditional approach to one that suits ID. The close collaboration of all the stakeholders starting as early as possible, assuring efficient bidirectional data flow, a correct division of BIM related tasks and responsibilities are one of the main cooperation issues that need to be dealt with and this inspired choice of the cooperation parameter (Azhar, 2011; Forsythe, 2014; Mäki & Kerosuo, 2015; Migilinskas et al., 2013).

Software - Software plays an important role in BIM implementation. There is a wide range of programs that can serve as the main tool for different project parties in this process. This allows for freedom of choice and from the business point of view assures competition between different software developing companies which have a positive impact on the product quality and pricing. On the other hand, this also introduces interoperability issues and creates a significant barrier to ensuring a fully circular and integrated process. Additionally, there is a need for some functionalities in certain contexts, such as small- and medium-sized contractors, that current software market does not satisfy (Malacarne et al., 2018; Migilinskas et al., 2013)

Skills - BIM-related methodologies require a certain set of skills from staff involved in a project. Proficiency in modeling and operating the BIM software is crucial for success but not easy to find in the market. Additionally, the "soft skills" of cooperating personnel are very important in ID. Many of the analyzed papers highlighted these and other skills as a significant barrier to BIM implementation (Arayici et al., 2011; Davies et al., 2017; Forsythe, 2014; Mäki & Kerosuo, 2015).

Costs - Especially in the context of SMEs, the surcharging costs concerning acquiring new software, hardware and time spent learning new skills can have a significant impact on the overall company's finances. This is an aspect that is very important from the perspective of a company that considers implementing this innovation (Forsythe, 2014; Malacarne et al., 2018; Migilinskas et al., 2013; Poirier et al., 2015b). In order to identify the scale and the relevant types of the barriers that lower SMEs BIM-adoption, the last column of Table 1 illustrates the importance of the described above categories that the sector might gain more from an attempt reducing their magnitude.

The category motivation has been considered and highlighted as a crucial one in most of the reviewed research papers. By good fortune, skepticism as well as confronting the innovative transformation obstacles (which are one of the main motivational barriers) are expected to be reduced with upcoming years (due to increased awareness) and by reducing the magnitude of the other obstacles. Lack of effective cooperation and BIM-related skills turns out to be the two other largest challenges. Insufficient knowledge of BIM processes and ICT principles can be considered a medium scale problem, subjected to considering that many of those barriers seem interconnected. More effective cooperation and a better skillset match of the project members (or a lower skill requirement) can be provided due to a decrease of misunderstandings (cooperation parameter), and more realistic perception of BIM (knowledge parameter). Additionally, enhancing and overcoming the skill barriers would also improve collaboration. This leads to a conclusion that focusing on overcoming skill and knowledge relevant challenges should have an echoing positive reaction on different issues as the implications of BIM implementation.

3.1 Information collected from Internet forums

In this subsection, we provide a few short examples of the information that were collected and analyses from internet forums. Due to the fact that most of the existing BIM-related forums focus on BIM-based software (i.e. Autodesk Revit), the data collection here has a narrow software focus.

Response from a user FBlome from www.revitforum.org. A self-employed residential architect from Menlo Park, California (USA) with many years of experience in the single-family housing sector

FBlome suggests that undertaking any initiatives which assume close collaboration between partners of a construction project is not plausible for the current state of this sector of the industry since it consists of many small businesses working independently that are not motivated to change their work ethic. "A few years ago," as the respondent states, he took part in a design-build project with a contractor/developer building a large high-end home. A BIM consultancy company (with experience in dealing with tract and spec home developers – design once, build many) was hired which purpose was to provide a BoM (Bill of Materials). The conclusions drawn from that cooperation were as follows:

- Creation of an accurate BoM in Revit is extremely time-consuming, especially in case of dealing with complex structural nuances;
- There was not a single subcontractor willing to take advantage of the created BoM for their pricing and bidding which defeated the whole purpose of the initiative.

Different sources

(…) if you are serious about cost estimation you cannot do it inside Revit. the problem lies within the fact that Revit accounts for materials and the work associated with them. Example, laying brick might require the brick be washed before laying it, that activity cost money. Concrete formwork requires materials and installation. Revit does not have any idea about that. – user smashta

Excerpted from a discussion under a thread titled "What's the best way to generate quantity and cost estimates?" on augi.com forum. ["What's the best way", 2011]

(…) I dislike moving between programs. This is unproductive, too. You have to learn multiple programs. In our case, there are Revit, Advance Steel, Civil3D, SOFiCAD and Inventor what should be learned to be productive. Why this is unproductive? Each program has its own User Interface, its own learning curve. And I even do not want to think over data exchange… – user m.steffannoe

Excerpted from a discussion under a thread titled "Measure in 3D" on autodesk.com forum. ["Measure in 3D", 2016].

All online forum sources provide consensual data about the fact that there is much room for improvement of BIM utilization during project phases that are the most relevant to them. BIM software is considered to have great potential, but it is difficult to utilize it correctly at its current state due to many of the barriers mentioned in the literature. For example, the collected data proves that in Autodesk's Revit there is a significant amount of space for improvement on various levels that could enhance the user experience by lowering the complexity of some tasks, i.e. major inefficiencies of the Autodesk Revit as extracted from the forums are as follows:

- QTO (Quantity Take-Off) and scheduling tools are considered inefficient by most;
- QTO tools suffer from many limitations for the user (filtering, handling of the finishes, handling

of some objects) which make them less applicable for precise measuring;

- Modeling and editing of certain elements are inefficient and time-consuming as a result. Forces to perform certain workarounds;
- Some Revit processes suffer from limited filtering options available;
- Interoperability with other software.

4. Discussion and results

In the last years, other researchers highlighted the significance of the investigation of BIM-adoption-related issues regarding SMEs. Dainty et al., (2017) claim that the endemic disadvantages that such companies face have been ignored in the policy process which – if not counteracted - is likely to increase the market differentiation. In their research, Miettinen & Paavola (2014) suggest that a well-documented investigation of BIM implementation within different contexts needs to be undertaken in order to assess problems and further challenges of developing the BIM use. This research attempts to take part in the aforementioned investigation.

The analysis model in the previous section reveals the challenges and their relative importance in shifting into BIM, especially in the context of SMEs. The last column of Table 1 allows making a general assessment about which of the analyzing parameters (challenges) play a more significant role in slowing down the process of BIM-adoption in the AECO sector in alignment with the surveyed literature. It is evident that the common skepticism attitude of SMEs and especially the contracting firms' representatives regarding BIM implementation is substantial.

n this consideration, the BIM-adoption barriers can be categorized in three groups concerning their scales including large-scale (motivation, cooperation, and skills), medium scale (knowledge), and small scale (software and cost-related challenges). This shows that although SMEs have significantly smaller investment capabilities in the sector, the financial aspect of a BIM transformation is not the biggest concern for these companies – on the contrary – it can be considered a minor obstacle in comparison to the rest of identified categories. Since associated software challenges are also less critical compared to others, it can result that software relevant aid for SMEs should not be excluded as possible support in BIM implementation for SMEs. In addition, focusing on the facilitation of collaboration processes and complexity reduction (skill requirement) by any means can be noticeably beneficial for the whole sector.

Software, skills & costs: Exploration of the BIM technology in the SMEs context proves that there is much room for improving its utilization in this sector, even more so, specifically on the contractors' end. Research results based on data collected from a wide range of sources demonstrate that among various factors BIM software is one of those that limit BIM-adoption on the AECO market and is correlated with different issues like skill and resource requirements. BIM software products, like Autodesk's Revit, as well as others, expand their toolsets rapidly to make them capable of creating more complex and demanding BIM models applicable to large-scale development projects. Since BIM software development is a business like any other, the product needs to satisfy the user's needs in order to sell and provide revenue. At the current state, the largest clients of those software development companies are the ones involved in the largest and most demanding of projects; hence the priority is put on satisfying this part of the sector. The SME sector must not be neglected with that regard.

However, BIM user's persona differs greatly depending on the part of the construction sector considered which results in the user's needs differing greatly throughout the large industry like this. The manifestation of that diversity can be observed when considering how many different software product propositions there are available on the market right now. The choice of BIM software is wide to such an extent that new consulting companies started to emerge which provide service of just researching and identifying BIM products fitting the needs provided by the client. Additionally, this situation works against the basic ID principle, namely the integration. Since BIM software is crucial in the process of switching from traditional construction to ID, the factor of the introduced stakeholder separation due to the utilization of numerous software platforms being a prerequisite of even a small-scale construction project works against this integration and should be minimized. Focusing on the reduction of the size of the required "BIM software starter-pack" for those at a BIM-infant state while still not forgetting about enhancing general interoperability of different software packages would contribute to enhancing BIM-adoption among SMEs.

Research results prove that an efficient BIM-software solution for SMEs requires putting more emphasis on different issues than in the case of large companies. SMEs working on small-scale projects do not encounter that much repetitiveness and scarcity of resources like cost, time, BIM-proficient staff and knowledge about alternative means of project delivery (like ID) which make smaller companies' BIM-use substantially different. Even though this sector constitutes a significant amount of the AECO industry the most popular BIM products on the market comprise of numerous solutions that SME users cannot fully take advantage of and lack simple solutions that could enhance BIM applicability greatly for small companies and consequently raise the BIM-adoption. More focus needs to be put on providing BIM-solutions that are less hardware-demanding, have a lower skill floor – the difficulty level of beginning the process of mastery of a specific computer program – and have a payment scheme that does not overburden smaller construction companies

Motivation, cooperation & knowledge: Other barriers, besides software-related, like motivation, cooperation and knowledge can be tackled with other means and enhance overall BIM implementation since all of the implementation barriers are correlated. Rising BIM awareness amongst smaller companies and fighting the belief that investing in BIM is profitable only for large companies is one of the ways that knowledge and motivation obstacles can be reduced. Klaschka's (2014) case studies serve as a good example of that since there is no believing without seeing when a businesses' future is at stake. Additionally, according to Alreshidi et al. (2017), BIM-related standards must not reflect the desires, issues, and concerns of specific groups (large companies) excluding others (SMEs). Inappropriate BIM-governance functions like a repellant to those of doubt. Undertaken literature review's results prove that the "BIM works only for large companies" a stereotype is wrong by providing real examples of SMEs gaining from BIM implementation, but those and other examples still need more publicity in order to help with a mindset change of the skeptics. Cooperating with stakeholders that are not willing to do so or lack either the skills or the knowledge of how it should be done cannot be optimal. Furthermore, software that does not fit into a project's context or scale or is just too expensive to implement exacerbates teamwork between the project's members. That is why the significance of the cooperation adoption barrier is mainly dependent on the scope of work put into dealing with the BIM transformation efficiently, with adequate preparation and the right team. Without those factors quality of teamwork suffers and can lead to piling up of BIM-related issues that can have the opposite effect to ensure the team of the validity of the decision to perform a BIM transformation.

Closing the BIM-gap: Closing the BIM-gap would provide many benefits to both SMEs and large construction companies. More small companies could get involved in demanding large-scale projects as sub-contractors and start implementing new ideas on other projects after taking part in an alternative project delivery method and utilizing modern technologies. Achieving that could expand their competences and range of provided services that would make those companies more resilient to construction market's fluctuations by better adaptation potential. On the other hand, large companies would get a wider range of competent sub-contractors to choose from when collecting the project team that can deal with a higher degree of complexity and more innovative workflows. All in all, the pace of the innovation adopting in the AECO industry would increase.

5. Conclusions and future work

This paper considered the common characteristics of various barriers that slow down the process of BIM-adoption in the AECO industry. Identification of these parameters allowed to create an analysis model which helped to get an overview of the collected data from the surveyed literature. Many of the barriers for enhancing the BIM-adoption in the market came out to be interconnected. This means that overcoming either of them can also cause in reducing another.

It is evident that close cooperation with practitioners when researching SMEs' BIM implementation is of great importance, likewise as isolation of this construction industry sector is one of the reasons for BIM-gap to emerge in the first place. Even though general BIM awareness on the market is high, BIM-gap awareness should be improved, and more attention should be given to it so as to market-wide BIM implementation can be accelerated and, hypothetically, it enhances the general construction sector's condition. From the Internet forum research, it was concluded that tailoring of the

BIM-software solutions to the needs of all building sector stakeholders plays a critical role in increasing the applicability of BIM-technologies for the SME sector. Further, software development should be undertaken, expanding its functionalities to avoid fragmentation of BIM processes when performing singular tasks in many different programs, reducing resource requirements (i.e. time) and skill requirement rooted in the level of complexity of certain procedures in BIM. The more repetitive and non-creative simple tasks can be automated, the more resources can be assigned to the other tasks.

References

Alreshidi, E., Mourshed, M. & Rezgui, Y. (2017). Factors for effective BIM governance. Journal of Building Engineering, 10, 89-101. https://doi.org/10.1016/j.jobe.2017.02.006

[Andrewg]. (2018, December 28). What's the best way to generate quantity and cost estimates [Online forum comment]? Retrieved from http://forums.augi.com/showthread.php?133957-What-s-the-best-way-to-generate-quantity-and-cost-estimates

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C., & Oreilly, K. (2011). BIM adoption and implementation for architectural practices. Structural Survey, 29(1), 7-25. https://doi.org/10.1108/02630801111118377

Azhar, S. (2011). Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. Leadership and Management in Engineering, 11(3), 241-252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127

Bargstädt, H. (2015). Challenges of BIM for Construction Site Operations. Procedia Engineering, 117, 52-59. https://doi.org/10.1016/j.proeng.2015.08.123

Dainty, A., Leiringer, R., Fernie, S., & Harty, C. (2017). BIM and the small construction firm: A critical perspective. Building Research & Information, 45(6), 696-709. https://doi.org/10.1080/09613218.2017.1293940

[Damo]. (2018, December 28) Measure in 3D [Online forum comment]. Retrieved from https://forums.autodesk.com/t5/revit-ideas/measure-in-3d/idi-p/6336588

Davies, K., Wilkinson, S., & Mcmeel, D. (2017). Baby Steps with BIM – Learning to Walk the Talk. Lean and Computing in Construction Congress - Volume 1: Proceedings of the Joint Conference on Computing in Construction (JC3), July 4-7, 2017, Heraklion, Greece, 399-406. https://doi.org/10.24728/JC3-2017/0253

Deutsch, R. (2011). BIM and integrated design: Strategies for architectural practice. Hoboken, NJ: John Wiley & Sons, Inc.

Eastman, C. (2018). BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. Hoboken, NJ: John Wiley & Sons, Inc.

Forsythe, P. (2014). The Case for BIM Uptake among Small Construction Contracting Businesses. Proceedings of the 31st International Symposium on Automation and Robotics in Construction and Mining (ISARC), July 9th to 11th, 2014, Sydney, Australia. https://doi.org/10.22260/isarc2014/0064

Ghaffarianhoseini, A., Rehman, A. U., Doan, D., Zhang, T., Ghaffarianhoseini, A., Naismith, N. & Tookey, J. (2016). A BIM Readiness & Implementation Strategy for SME Construction Companies in the UK. Proc. of the 33rd CIB W78 Conference 2016, Oct. 31st – Nov. 2nd, 2016, Brisbane, Australia, 696-709. https://doi.org/10.1080/09613218.2017.1293940

Groat, L., & Wang, D. (2002). Architectural Research Methods. Hoboken, NJ: John Wiley & Sons, Inc.

Holtz, P., Kronberger, N., & Wagner, W. (2012). Analyzing Internet Forums. Journal of Media Psychology, 24(2), 55-66. https://doi.org/10.1027/1864-1105/a000062

Kamari A., Christensen M. L., Jensen S., Petersen S. & Kirkegaard P. H. (2018a). A hybrid decision support system for generation of holistic renovation scenarios – cases of energy consumption, investment cost, and thermal indoor comfort. Sustainability 2018, 10(4), 1-23. https://doi.org/10.3390/su10041255

Kamari A., Laustsen C., Petersen S. & Kirkegaard P. H. (2018b). A BIM-based decision support system for the evaluation of holistic renovation scenarios. Journal of Information Technology in Construction 23, 354-380. Retrieved from https://www.itcon.org/2018/18

Kamari A., Corrao R., Petersen S. & Kirkegaard P. H. (2018c). Tectonic Sustainable Building Design for the development of renovation scenarios—Analysis of ten European renovation research projects Proc. Int. Conf. on Seismic and Energy Renovation for Sustainable Cities. Proc. of The Seismic and Energy Renovation for Sustainable Cities - SER4SC 2018 Conference, 1–3 February, 2018, Catania, Italy, 645–656

Klaschka, R. (2016). BIM in small practices illustrated case studies. Newcastle upon Tyne, UK: NBS.

Krygiel, E., & Nies, B. (2008). Green BIM: Successful sustainable design with building information modeling. Indianapolis, Ind: Wiley Technology Pub.

Lu, S.L., Sexton, M.G. & Abbot, C. (2008). Key characteristics of small construction firms: A United Kingdom perspective. Proceedings of CIBW065/055 Joint International Symposium: Transformation through Construction, Dubai, UAE, 15–17 November. https://doi.org/10.1080/09613210500254474

Mäki, T., & Kerosuo, H. (2015). Site managers' daily work and the uses of building information modelling in construction site management. Construction Management and Economics, 33(3), 163-175. https://doi.org/10.1080/01446193.2015.1028953

Malacarne, G., Toller, G., Marcher, C., Riedl, M., & Matt, D. T. (2018). Investigating benefits and criticisms of BIM for construction scheduling in SMES: An Italian case study. International Journal of Sustainable Development and Planning, 13(01), 139-150. https://doi.org/10.2495/SDP-V13-N1-139-150

Miettinen, R., & Paavola, S. (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. Automation in Construction, 43, 84-91. https://doi.org/10.1016/j.autcon.2014.03.009

Migilinskas, D., Popov, V., Juocevicius, V., & Ustinovichius, L. (2013). The Benefits, Obstacles and Problems of Practical Bim Implementation. Procedia Engineering, 57, 767-774. https://doi.org/10.1016/j.proeng.2013.04.097

NBS. (2016). NBS International BIM Report 2016. Retrieved February 15, 2019, from https://www.thenbs.com/knowledge/nbs-international-bim-report-2016

NBS. (2018). NBS National BIM Report 2018. Retrieved February 15, 2019, from https://www.thenbs.com/knowledge/nbs-national-bim-report-2018

Poirier, E. A., Staub-French, S., & Forgues, D. (2015b). Assessing the performance of the building information modeling (BIM) implementation process within a small specialty contracting enterprise. Canadian Journal of Civil Engineering, 42(10), 766-778. https://doi.org/10.1139/cjce-2014-0484

Poirier, E., Staub-French, S. & Forgues, D. (2015a). Embedded contexts of innovation. Construction Innovation. 15(1), 42-65. https://doi.org/10.1108/CI-01-2014-0013

A framework for studying the factors that influence the BIM adoption process

Elodie Hochscheid[1, *] and Gilles Halin[1]
[1]MAP-CRAI (UMR 3495 CNRS/MC), ENSA Nancy, Nancy, France
[*]email : elodie.h@crai.archi.fr

Abstract

Building Information Modeling/Management (BIM) is an emerging technological and procedural innovation within the Architectural, Engineering, Construction and Operation (AECO) industry. Adoption of BIM has increased significantly over the last few years and BIM adoption is an active research area that aims to construct a better understanding of the spread of BIM and factors that may explain the speed of BIM adoption and its diffusion. Unfortunately, in this literature, the factors that influence the adoption process are unclear: those who influence the decision to adopt (Decision Factors or DFs) are confused with those that influence the success of the implementation (Implementation Factors or IFs). IFs are very rarely studied, although they could make it possible to produce recommendations to help firms to implement BIM. This paper aims to identify the elements that can influence the BIM adoption process. The main findings of this paper is a classification model of innovation adoption influencing factors, a critical view of methods used to study BIM adoption factors, and an overview of factors that can influence the adoption of BIM, including DFs and IFs.

Keywords: BIM adoption, framework, influencing factors, barrier, driver.

1. Introduction

Building Information Modeling/Management (BIM) is an emerging technological and procedural innovation within the Architectural, Engineering, Construction and Operation (AECO) industry. Adoption of BIM has increased significantly over the last few years and is now an active research area. It aims to construct a better understanding of the spread of BIM and factors that may explain the speed of BIM adoption and its diffusion. Our understanding of the BIM adoption process has recently evolved, through the *Diffusion of innovation theory*. It is described in a five-stages process that opens up new (as yet untapped) perspectives for the study of BIM Adoption Influencing Factors (BIM-AIFs). It reveals that some of BIM-AIFs are not taken into account in the BIM adoption literature.

In a **first section**, the model of the adoption process is briefly introduced. It brings out the difference between two types of BIM-AIFs: those who intervene before and after the decision of adoption. The value of this distinction and reasons of its absence in BIM-specific literature are explored.

In a **second section**, literature on innovation is investigated, taking into account the distinction made in the first section. Factors that may be involved in innovation adoption are identified and classified to facilitate the study of specific innovation (as BIM). As a methodology, we started from the generic literature to avoid omissions that may appear in the BIM-specific literature.

In a **third section**, BIM-specific literature that explore BIM-AIFs is investigated to identify methodology strengths and unexplored opportunities for the study of BIM-AIFs.

As main findings, this paper proposes a framework that can be exploited for the study of BIM-AIFs. This framework takes into account non-BIM-specific literature, recent distinctions made in the BIM adoption area and a critical analysis of the methods used today to study BIM-AIFs.

2. The BIM adoption process and what impacts it

In this section, the model of the adoption process is briefly introduced. Possibilities that emerge from this model and reasons why they have not yet been studied are explored.

2.1 The BIM adoption process

As BIM is an innovation, its spread follows the generic models of the diffusion, adoption and implementation of innovations. BIM adoption is here described in a **five-stage process** (Hochscheid & Halin, 2019a) (fig. 1), as in the Diffusion of Innovation Theory (Rogers, 2003). This process begins when possible adopters become aware of the existence of BIM (fig. 1, stage 1), evaluate the possibility of using it (stage 2), and take a decision: to adopt or to reject it (stage 3). If **decision of adoption** is made, adopters undertake a set of activities to deploy BIM processes, tools and methods (stage 4), and need time to anchor these new uses and practices in their habits (stage 5).

Key moments **milestone** this process: **Decision of Adoption (DoA)** is the moment when stakeholders make a commitment to start implementing BIM, **Effective Implementation (EI)** is when stakeholders have tested and used BIM on a part of their production, **Confirmation of Adoption (CoA)** refers to the moment when stakeholders have anchored BIM in their practice, reached a certain level of mastery of it and have indicated their willingness to continue.

This process can however stop at different moments (**Adoption failures**), including during implementation (Klein & Sorra, 1996). Factors affect the continuation, speed, and cessation of the whole adoption process, here called "**BIM adoption influencing factors**" (BIM-AIFs) are considered differently depending on whether they occur before or after the DoA.

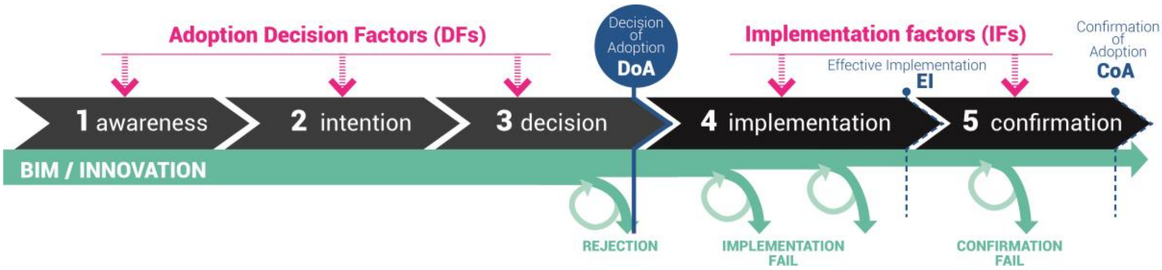


Figure 1: Model of the BIM adoption process, adapted from (Hochscheid & Halin, 2019a)

2.2 BIM-AIFs: before and after DoA

The DoA (fig. 1) appears to be a turning point in the adoption process. Potential adopters move from a period in which they will need elements to position themselves to make a decision (before DoA) to a period in which they need to achieve an objective they have set for themselves: acquire some mastery of BIM (after DoA). Factors that intervene in the adoption process **before the DoA** (Decision Factors / DFs) therefore influence the **decision-making period** whereas factors that intervene **after the DoA** (Implementation Factors / IFs) will influence **the success of implementation** and the anchoring of new practices. Both DFs and IFs intervene during the adoption process (and are therefore BIM-AIFs), but they do not concern the same phenomena, and must be differentiated. However, it seems that the difference between DFs and IFs is not explicitly made in BIM adoption literature. The study of the factors that influence the adoption of BIM has rarely been completed with a clear differentiation between the stages of the adoption process, except for very recent work (A. L. Ahmed & Kassem, 2018). Thus, the study of factors that influence BIM adoption have often been confined to the study of DFs. Some hypotheses are put forward here to explain this.

First, it should be noted that Rogers' five-stages model (Rogers, 2003) concerns the *innovation-decision process*. This model focuses on the *decision* to adopt: even the confirmation stage refers to confirmation of *decision*. Although this is a seminal work, many research have criticized the Diffusion of Innovation theory, in particular on the vagueness left in the definition of the term "adoption" (Bayer

& Melone, 1989). The concept of *adoption* has several and contradicting definitions (A. L. Ahmed & Kassem, 2018; Hochscheid & Halin, 2019a). It is often considered that adoption is synonymous with a decision to adopt (Mohammad, Abdullah, Ismail, & Takim, 2017), but recent work considers that adoption is a process that includes implementation (A. Ahmed, Kawalek, & Kassem, 2017). Recently, a study has aggregated BIM-AIFs by positioning them on the adoption process. The authors indicated, by addressing only the first three phases of the process, that they focused on DFs (A. L. Ahmed & Kassem, 2018). It is a step towards understanding the adoption process and the demarcation between DFs and IFs.

Theories of technology adoption were exploited very early on to study BIM-AIFs. These theories describe and explain how individuals choose a technology. After being investigated in a few research, BIM-AIFs extracted from these theories were aggregated in literature reviews and synthesis on the factors that influence the adoption of BIM (A. Ahmed & al 2017; Ahuja, Sawhney, Jain, Arif, & Rakshit, 2018). These syntheses have led to a consensus on the BIM-AIFs that do not include IFs.

It is also possible the difficulty that companies have in implementing BIM has been underestimated. It would seem that we considered that making the decision to adopt would necessarily lead to successful implementation, hence the fact that DFs have been more studied than IFs. But the adoption process can stop between the DoA and CoA, hence the interest of studying IFs.

As a conclusion for this section, we note that there is a significant difference between DFs and IFs. However, this difference has only rarely been exploited in the BIM literature where BIM-AIFs have often been summarized to DFs. This omission may be explained in different ways, but probably finds its source in the confusion about the definition of the word *adoption*, which has long been considered synonymous with *decision to adopt*.

3. Classification of BIM Adoption Influencing Factors (BIM-AIFs)

This section is a non-BIM-related literature review that gives an overview of factors that may influence adoption of an innovation. Studies focusing more on the elements that influence the decision of adopters (individuals and organizations) have been treated separately from those that attempt to analyze the success factors of implementing an innovation in an organization. The elements proposed here are a follow-up to previous work (Hochscheid & Halin, 2019a), but they are here supplemented and structured. The identified **factors** have been classified into different **fields** and **categories**, according to the model presented in fig. 2.

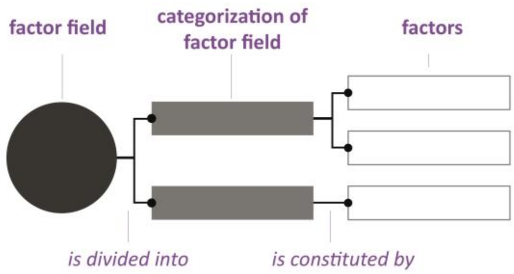
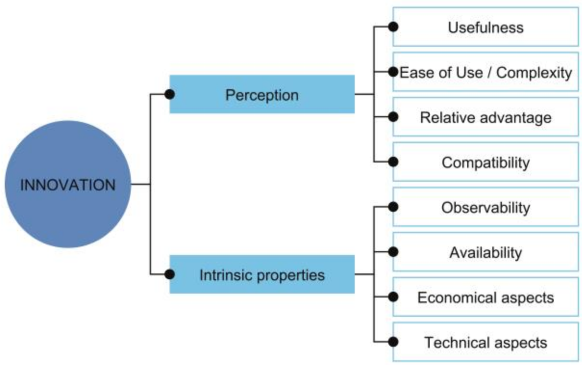


Figure 2: classification model of innovation adoption influencing factors

3.1 Why do people choose to use an innovation?

A consensus is beginning to emerge on the generic factors that influence the decision to adopt a technology. Presented in different ways in the literature on innovation (Waarts, van Everdingen, & van Hillegersberg, 2002), they can be classified in three factor fields: characteristics of the innovation, internal context of the firm and external context of the firm.

Characteristics of the innovation that play an important role in the choice of this innovation has been described in seminal work of Rogers, in the first edition of Diffusion of Innovation, in 1962. Five attributes of innovation are considered: (1) **relative advantage**, *"the degree to which an innovation is perceived as being better than the idea it supersedes"*; (2) **compatibility**, *"the degree to which an innovation is perceived as consistent with the existing values"*; (3) **complexity** *"the degree to which an innovation is perceived as relatively difficult to understand and use"*; (4) **trialability**, *"the degree to which an innovation may be experimented with on a limited basis"*; (5) **observability**, *"the degree to which the results of an innovation are visible to others"*. Around the 90's and 2000's, research in sociological psychology area focused on user adoption and acceptance of technology with several models called *Technology adoption models* (Collan & Tétard, 2011). These theories evoke (among other things) characteristics of the innovation that can be involved in technology selection: (6) **perceived usefulness**, (7) **perceived ease of use**), (8) **technical and** (9) **economical aspects** of the technology. Among the factors mentioned here, some concern the **perception that potential users have of innovation** (1,2,3,6,7), others concern the **intrinsic characteristics of the innovation**, identical for all potential users (4,5,8,9), see fig.3.



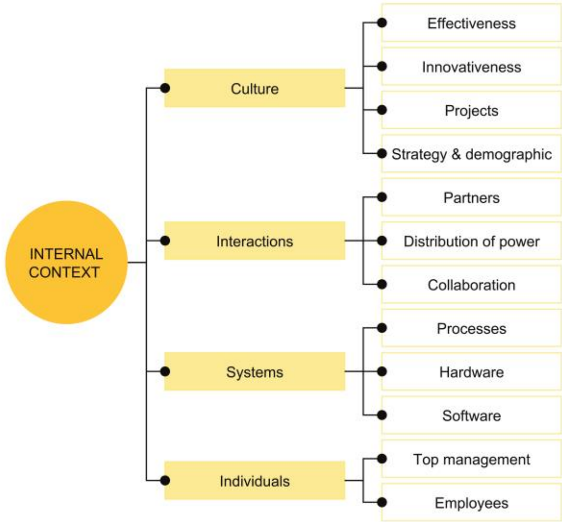


Figure 3 (left): classification of adoption influencing factors for "innovation characteristics" field

Figure 4 (right): classification of adoption influencing factors for "firm's internal context" field

Internal context of the firm refers to all elements that constitute the firm from the point of view of human relations and the material context of work. The constituent elements of a firm presented here are the result of previous literature review synthesis (Hochscheid & Halin, 2019a). The influence of the internal context of organizations for technology selection has been studied in several disciplinary fields and theories. The abovementioned *Adoption Theories* also focused on (1) **individuals** and personal characteristics that can influence their willingness to use a technology. *Population ecology theory* (Hannan & Freeman, 1977) indicates that previous choices made in the firm for (2) **systems** and staff created internal inertia that impacts future technological choices. In extreme cases, these previous choices may totally prevent an individual or a firm from changing technology (Arthur, 1989; Liebowitz & Margolis, 1995). Individuals react differently to innovations, depending on their experience, seniority, career stage, and skills (Mintzberg & Westley, 1992; Sainsaulieu & Segrestin, 1986). Internal political constraints and history of the firm (firm's (3) **culture**), and (4) **interactions** within the firm, participate to this inertia and influences the perceived ease of implementation and decision to adopt. all the above-mentioned elements are summarized in fig. 4.

External context of the firm refers to social, economic, political and competitive environment of the firm. Organizations need to be pushed by external forces to change (Hannan and Freeman (1977), as legal barriers, information channels, legitimacy constraints and collective problems. *Institutional theory* (DiMaggio & Powell, 2000) classifies these forces in three types : (1) **coercive isomorphism** (formal and informal pressures from government and other organizations) , (2) **mimetic processes**

(when organizations model themselves on other organizations), and (3) **normative pressures** (sharing and normalization of conditions and methods of work). They are here referred to as "forces". It is possible to differentiate between those that apply directly from the external context (1 and 3), and another one that the actors apply to themselves (2), see fig.5.

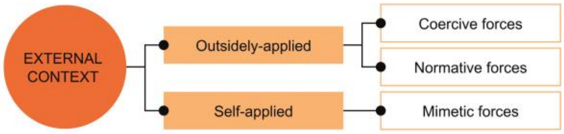


Figure 5: classification of adoption influencing factors for "firm's external context" field

This section presents a classification of generic factors that influence the decision to adopt a technology. In the BIM-specific literature, (A. L. Ahmed & Kassem, 2018) arrive at a very similar classification on the basis of an extensive state of the art of literature specific to the BIM. These factors have therefore, on the whole, already been addressed in the BIM literature.

3.2 What influences the success of innovation implementation in a firm?

Much work in the field of management has focused on how an organization can implement change Hannan and Freeman (1984) identified factors that may affect mortality of firms due to change. According to them, *characteristics of a company* (i.e., size, age-specialized, or generalist), *external environment* (i.e., stable, uncertain), and the *implementation method for change* (i.e., type, speed) are involved. Pettigrew (2012), developed the "receptive" and "non-receptive" concept for change context in a firm, and pointed out that "*environmental pressure, a supportive organizational culture, the quality and coherence of policy, key people leading change, the change agenda and its locale, the quality of managerial clinical relations, simplicity and clarity of change goals, and co-operative inter-organizational relationships*" are eight signs that seem to be associated with a faster pace of change. These work are in line with the conclusions of a previous qualitative study of the BIM implementation (Hochscheid & Halin, 2018) that identified IFs : implementation time management, change agents chosen, previous habits, availability of BIM-educated professionals, type of projects made by the firm, training process, the firm's culture, project teams, and external partners. In this section, a non-BIM-specific literature is therefore explored to identify and classify possible IFs.

On the basis of the elements presented above, it is here proposed to examine the following fields : **characteristics of the innovation**, **internal context of the firm**, **external context of the firm**, and **characteristics of change**. Pettigrew (1987) also evokes the role of chance and surprise in this process. Let us keep this in mind to remind ourselves that change within a firm is a very complex process that certainly cannot be predicted or fully modeled.

Characteristics of the innovation that influence decision to adopt described in the previous section (fig. 3) may also influence implementation and confirmation. The **subjective part of these characteristics** (if the innovation is perceived useless or too complex for example) will influence individual's motivation for implementation and can cause high resistance to change during implementation (Kotter & Schlesinger, 1989). **Intrinsic properties** of innovation can influence individual's perception of it (Klein & Sorra, 1996) and can be directly involved during implementation, for example when individuals are confronted with interoperability problems (technical aspects), lack of help and tutorials (observability, availability), or an insufficient return on investment (economical aspects) (Hochscheid & Halin, 2018).

Internal context of the firm's impact on successful change (and therefore during the implementation) has been highlighted in several research (Franklin, 1976; Johnson, 1992; Kim, 1998; Pettigrew, 1987, 2012). Mintzberg & Westley (1992) identified different levels of change in an organization: culture, structure, systems, people, vision, positions programs and facilities. The firm's **culture** can, for example, integrate a general openness to innovation and an active and permanent desire to improve effectiveness, which facilitates implementation. Demographic characteristics of the firm (number of employees, projects size, number of hierarchical levels), **interactions** within the firm (between top-management and employees) or relations with partners can boost or lower implementation easiness (Laforet, 2013). As indicated in previous section, the nature and functioning of previous **systems** and characteristics of **individuals** (i.e. tolerance to change) also play a role in the ease of implementation. All the levels of the company presented above (fig.4) are therefore involved in the decision to adopt as well as in the implementation process.

External context of the firm can impact change implementation at different levels (Franklin, 1976; Pettigrew, 1987). Conditions of demands, sharing and exploration of innovation with partners and clients (**normative forces, coercive forces**) can encourage or discourage people for implementation (Pettigrew, 2012). The availability of implementation protocols (**normative forces**) or possibility for firms to identify good practices through other firms that have already taken the plunge (**mimetic forces**) impacts ease of implementation. These three factors have been put in place to explain decision to adopt BIM (fig 5), but can be translated into IFs as well.

Change characteristics refers to the way in which change is implemented in the company. Change management in the company is essential to the success of the implementation. Main components of change that play a role in the success of implementation are here extracted of change management literature, and classified in three main categories, according to (Hochscheid & Halin, 2019b) (fig. 6).

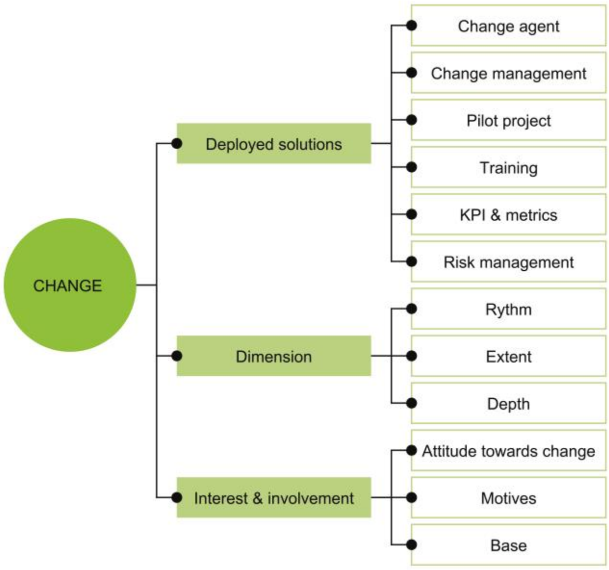


Figure 6: classification of adoption influencing factors for "change characteristics" field

(1) Dimension of change represents the breadth of change in three axes, based on Giroux's (1991) topology of change : (a) the time and duration of change (**rhythm**) (Kotter & Cohen, 2002), (b) the **extent** of change within the company (Pettigrew, 1987), (c) the distance between previous practices and new practices, which refers to the amount of change to be made (**depth**). **(2) Interest and involvement** of individuals (top management and employees) in change matches three aspects: (a) **attitude of individuals towards change** and climate in the firm that can lead to resistance or openness to change (Franklin, 1976; Johnson, 1992; Klein & Sorra, 1996)), (b) **motives** and commitment that led to implementation effectiveness (Greenwood & Hinings, 1988; Klein & Sorra, 1996), (c) **base**, which refers internal dynamics related to the change (top-down or bottom-up). **(3) The practical solutions that can be deployed** within the firm to manage implementation of an innovation were the subject of further study in (Hochscheid & Halin, 2019b). These are here summarized in six categories : (a) **change management**, refers to the way change is organized (needs assessment, transition planning, evolution of the firm's strategy, staff and team management), (b) characteristics of the **change agent** (Franklin, 1976**)**, which is the person or group that leads implementation in the firm and who can from inside and outside of the firm (both are needed (Johnson, 1992)**,** (c) the first project on which tests are made (**pilot project**), (d) the **training** progress, topics, and assessment of internal standards, (e) **Metrics** (key performance indicators and maturity metrics), and (f) **risk management** for the firm towards implementation.

3.3 Synthesis

In this section, factors that intervene throughout the adoption process (DFs and IFs) have been identified and classified, on the basis of literature area not related to a specific innovation. The respective literatures associated with these two types of factors are different and bring out factors that are expressed differently. It appears that the main areas involved in the adoption process are: the **internal context** of the firm, the **external context** of the firm, the **innovation characteristics**, and the **change characteristics**. Change characteristics only concern the implementation and confirmation phases of the adoption process (IFs), whereas the three other factor fields concern both DFs and IFs. The classification model of factors proposed here is very similar to the taxonomy proposed by (A. L. Ahmed & Kassem, 2018), which covers the first three phases of the adoption process (and therefore only the DFs). However, in this paper, an additional level of classification is proposed and the entire adoption process is covered. This overview includes a wide variety of factors involved in innovation adoption process and is intended to be used for the study of innovation adoption process.

4. BIM Adoption influencing factors

The previous section provides an overview and structuration of the factors involved during a generic innovation adoption process. In this section, the way this topic is handled in BIM-specific literature is explored; with an emphasis on the methodologies used rather than the results obtained.

4.1 A critical view of the methods used for the study of BIM-AIFs

Several theories and fields that make it possible to study the adoption of an innovation have been presented previously. BIM studies on adoption influencing factors are generally mono-oriented: it

focus on one theory or one field but does not offer an overview. *Technology adoption theories* are for instance investigated in (Lee, Yu, & Jeong, 2015; Son, Lee, & Kim, 2015), *institutional theory* are covered in (Cao Dongping, Li Heng, & Wang Guangbin, 2014). However, some recent studies undertake a classification of factors and propose an overview to get a research framework, notably technological, environmental, and organizational fields of influencing factors (A. Ahmed et al., 2017; Ahuja et al., 2018). *Change characteristics* don't seem to appear in a structured way in BIM-specific literature, even if some change-related factors are mentioned (Aibinu & Venkatesh, 2014).

BIM-AIF are seldom positioned on the adoption process. However, it has been shown that the significance of the impact of a factor depends on the stage of the adoption process concerned (A. L. Ahmed & Kassem, 2018). This impact also depends on the diffusion process (Waarts et al., 2002). For instance, the adopters who decided to adopt BIM 5 years ago were not driven by the same reasons (factors) as those that are doing it today. But taking into account all these parameters (factor field, adoption stage, positioning in relation to the diffusion process) makes the study very complex.

Methodologies used in BIM-specific literature to study these factors are varied. Most studies carry out a *literature review* to identify factors that influence the adoption of an innovation, and include at least one theory or field mentioned above. To identify the factors that influence the adoption of BIM specifically, some studies use *qualitative methods* (i.e. interviews, action research (Bin Zakaria, Mohamed Ali, Tarmizi Haron, Marshall-Ponting, & Abd Hamid, 2013)), but most of them exploit *quantitative methods*. Studies that combine qualitative and quantitative approaches are rare (Aibinu & Venkatesh, 2014; Cao Dongping et al., 2014). The number of respondents for the *questionnaire surveys* (quantitative) is generally relatively small (137 for (Cao Dongping et al., 2014), 125 in (Acquah, Eyiah, & Oteng, 2018), 184 in (Ahuja et al., 2018), 102 (Arunkumar, Suveetha, & Ramesh, 2018). Quantitative research generally provide in-depth statistical analysis to study relations (correlations) that can exist between the different factors (correlation matrix, Pearson's chi-squared test, Cronbach coefficient, Spearman’s rho coefficient, or the Kendall’s Tau coefficient).

The vocabulary used for describing BIM-AIFs is wide and varies from one paper to another: they can be referred to as factors, determinants, drivers, or barriers. It is sometimes considered that *factors* can take two forms: *drivers* (if they positively influence adoption) or *barriers* (when they hinder adoption) (Ahuja et al., 2018). Some research focus exclusively on barriers (Hosseini, Pärn, Edwards, Papadonikolaki, & Oraee, 2018; Olawumi, Chan, Wong, & Chan, 2018) or drivers. There is research that differentiates between the two and addresses both (Abubakar, Ibrahim, Kado, & Bala, 2014; Arunkumar et al., 2018). The wording given to the factors makes it possible to know whether the impact studied is *a priori* rather negative (i.e.” absent harmonization between standards”) positive (i.e. “efficient interoperability”), or neutral (i.e. “interoperability”). However, this can have a strong impact in a questionnaire survey because respondents can be influenced by the question’s wording.

4.2 Synthesis

Studying BIM-AIFs is difficult because it depends on many different elements such as the stage of the adoption process and the dissemination process. Many studies carry out literature review to find factors that may influence adoption, but provide only a partial view of these factors. This underlines the need of a framework for the study of BIM-AIFs. The explored approaches (qualitative, quantitative) are varied but rarely combined in a single study, while a variety of methods might produce interesting new results. Also, if we note that a lot of literature review work has already been done on DFs, it seems that IFs are very little conceptualized. Lastly, the way the factor is worded is important and can convey the kind of impact the factor may have. We therefore propose to extend the classification model (fig. 2) to include the *factor’s expression* and its *properties* (fig. 7) (positive formulation: *driver*, neutral formulation: *determinant*, negative formulation : *barrier*).

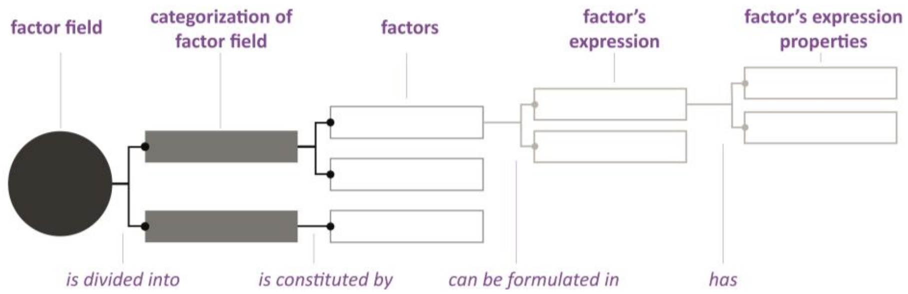


Figure 7: classification model of innovation adoption influencing factors (extended)

5. Conclusion

Adoption is here presented in a five-stages process from which we can deduce two main parts: the **decision part** and the **implementation part**. These two parts do not refer to the same phenomenon among adopters and the factors that influence them must therefore be differentiated. BIM adoption influencing factors (BIM-AIFs) may address users' decision to start using BIM (**Decision Factors**, **DFs**), or the success of the implementation (**Implementation Factors, IFs**). This distinction is fundamental because DFs cannot by themselves explain the speed of diffusion, while BIM-specific literature, though, seems to focus exclusively on DFs. *Adoption* has, indeed, often been considered synonymous with *decision-making*. This paper provides an overview of DFs and IFs, by investigating non-BIM-specific literature. The latter have been classified in **four fields of influence**: **internal context** of the firm, **external context of the firm**, **characteristics of the innovation** and **characteristics of change**. There is overlap between the two types of factors within these fields, but depending on whether they are DFs or IFs, they do not seem to operate in the same way. Research on BIM-AIFs mainly provide partial view of these factors, by confining oneself to the study of a single field, or only to the decision part of the adoption process. This underlines the need of a framework for the study of BIM-AIFs. Also, the distinction between factors that act negatively (barriers) or positively (drivers) is sometimes not made although it can play a predominant role, especially in questionnaire surveys. This research therefore proposes a complete framework for the study of BIM-AIFs. The authors have already used this framework to create a questionnaire, in which both DFs and IFs are addressed, and distinction between barriers and drivers is made.

References

Abubakar, M., Ibrahim, Y. M., Kado, D., & Bala, K. (2014). Contractors' perception of the factors affecting building information modelling (BIM) adoption in the Nigerian construction industry. *International Conference on Computing in Civil and Building Engineering*, 23–25.

Acquah, R., Eyiah, A. K., & Oteng, D. (2018). Acceptance of Building Information Modelling: a survey of professionals in the construction industry in Ghana. *Journal of Information Technology in Construction (ITcon)*, *23*(4), 75-91.

Ahmed, A., Kawalek, P., & Kassem, M. (2017). A Conceptual Model for Investigating BIM Adoption by Organisations. *Proceedings of the Joint Conference on Computing in Construction (JC3), Volume I*, 447-455. https://doi.org/10.24928/JC3-2017/0103

Ahmed, A. L., & Kassem, M. (2018). A unified BIM adoption taxonomy: Conceptual development, empirical validation and application. *Automation in Construction*, *96*, 103–127.

Ahuja, R., Sawhney, A., Jain, M., Arif, M., & Rakshit, S. (2018). Factors influencing BIM adoption in emerging markets–the case of India. *International Journal of Construction Management*, 1–12.

Aibinu, A., & Venkatesh, S. (2014). Status of BIM Adoption and the BIM Experience of Cost Consultants in Australia. *Journal of Professional Issues in Engineering Education and Practice*, *140*(3), 04013021. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000193

Arthur, W. B. (1989). Competing technologies, increasing returns, and lock-in by historical events. *The economic journal*, *99*(394), 116–131.

Arunkumar, S., Suveetha, V., & Ramesh, A. (2018). A feasibility study on the implementation of building information modeling (BIM): from the architects' & engineers' perspective. *Asian Journal of Civil Engineering*, *19*(2), 239-247. https://doi.org/10.1007/s42107-018-0020-9

Bayer, J., & Melone, N. (1989). A critique of diffusion theory as a managerial framework for understanding adoption of software engineering innovations. *Journal of Systems and Software*, *9*(2), 161–166.

Bin Zakaria, Z., Mohamed Ali, N., Tarmizi Haron, A., Marshall-Ponting, A. J., & Abd Hamid, Z. (2013). Exploring the adoption of Building Information Modelling (BIM) in the Malaysian construction industry: A qualitative approach. *International Journal of Research in Engineering and Technology*, *2*, 384-395.

Cao Dongping, Li Heng, & Wang Guangbin. (2014). Impacts of Isomorphic Pressures on BIM Adoption in Construction Projects. *Journal of Construction Engineering and Management*, *140*(12), 04014056. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000903

Collan, M., & Tétard, F. (2011). Lazy User Model: solution selection and discussion about switching costs. *Scandinavian Conference on Information Systems*, 56–68. Springer.

DiMaggio, P. J., & Powell, W. W. (2000). The iron cage revisited institutional isomorphism and collective rationality in organizational fields. In *Economics Meets Sociology in Strategic Management* (p. 143–166). Emerald Group Publishing Limited.

Franklin, J. L. (1976). Characteristics of successful and unsuccessful organization development. *The Journal of Applied Behavioral Science*, *12*(4), 471–492.

Giroux, N. (1991). La gestion du changement stratégique. *Gestion*, *16*(2), 8-14.

Greenwood, R., & Hinings, C. R. (1988). Organizational design types, tracks and the dynamics of strategic change. *Organization studies*, *9*(3), 293–316.

Hannan, M. T., & Freeman, J. (1977). The population ecology of organizations. *American journal of sociology*, *82*(5), 929–964.

Hannan, M. T., & Freeman, J. (1984). Structural inertia and organizational change. *American sociological review*, 149–164.

Hochscheid, E., & Halin, G. (2018). BIM implementation in architecture firms : Interviews,case studies and action research used to build a method that facilitates implementation of BIM processes and tools. *Proceedings of the 36th eCAADe annual conference*, 10. Lodz, Poland.

Hochscheid, E., & Halin, G. (2019a). Generic and SME-specific factors that influence the BIM adoption process: An overview that highlights gaps in the literature. *Frontiers of Engineering Management*, [PENDING PUBLICATION].

Hochscheid, E., & Halin, G. (2019b). *Micro BIM adoption in design firms: Guidelines for doing a BIM implementation plan*. Creative Construction Conference 2019 (CCC2019), Budapest, Hungary, [PENDING PUBLICATION].

Hosseini, R., Pärn, E., Edwards, D., Papadonikolaki, E., & Oraee, M. (2018). Roadmap to Mature BIM Use in Australian SMEs: Competitive Dynamics Perspective. *Journal of Management in Engineering*, *34*(5), 05018008.

Johnson, G. (1992). Managing strategic change—strategy, culture and action. *Long range planning*, *25*(1), 28–36.

Kim, D. H. (1998). The link between individual and organizational learning. *The strategic management of intellectual capital*, *41*, 62.

Klein, K. J., & Sorra, J. S. (1996). The challenge of innovation implementation. *Academy of management review*, *21*(4), 1055–1080.

Kotter, J. P., & Cohen, D. S. (2002). *The heart of change: Real-life stories of how people change their organizations*. Harvard Business Press.

Kotter, J. P., & Schlesinger, L. A. (1989). Choosing strategies for change. In *Readings in Strategic Management* (p. 294–306). Springer.

Laforet, S. (2013). Organizational innovation outcomes in SMEs: Effects of age, size, and sector. *Journal of World business*, *48*(4), 490–502.

Lee, S., Yu, J., & Jeong, D. (2015). BIM Acceptance Model in Construction Organizations. *Journal of Management in Engineering*, *31*(3), 04014048. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000252

Liebowitz, S. J., & Margolis, S. E. (1995). Path dependence, lock-in, and history. *JL Econ. & Org.*, *11*, 205.

Mintzberg, H., & Westley, F. (1992). Cycles of organizational change. *Strategic management journal*, *13*(S2), 39–59.

Mohammad, W. W., Abdullah, M. R., Ismail, S., & Takim, R. (2017). Overview of Building Information Modelling (BIM) adoption factors for construction organisations. *IOP Conference Series: Earth and Environmental Science*, *140*, 012107. IOP Publishing.

Olawumi, T. O., Chan, D. W., Wong, J. K., & Chan, A. P. (2018). Barriers to the integration of BIM and sustainability practices in construction projects: A Delphi survey of international experts. *Journal of Building Engineering*, *20*, 60–71.

Pettigrew, A. M. (1987). Context and action in the transformation of the firm. *Journal of management studies*, *24*(6), 649–670.

Pettigrew, A. M. (2012). Context and action in the transformation of the firm: A reprise. *Journal of Management Studies*, *49*(7), 1304–1328.

Rogers, E. M. (2003). *Diffusion of Innovations, 5th Edition*. Simon and Schuster.

Sainsaulieu, R., & Segrestin, D. (1986). Vers une théorie sociologique de l'entreprise. *Sociologie du Travail*, *28*(3), 335-352.

Son, H., Lee, S., & Kim, C. (2015). What drives the adoption of building information modeling in design organizations? An empirical investigation of the antecedents affecting architects' behavioral intentions. *Automation in Construction*, *49*, 92-99. https://doi.org/10.1016/j.autcon.2014.10.012

Waarts, E., van Everdingen, Y. M., & van Hillegersberg, J. (2002). The dynamics of factors affecting the adoption of innovations. *Journal of Product Innovation Management*, *19*(6), 412-423. https://doi.org/10.1016/S0737-6782(02)00175-3

The Enhancement of Design Business Operation Using LOD 350: The Case of China

Tianlun Yang[1, *], Georgios Kapogiannis[1, *], Byung Gyoo Kang[1] and Robin Wilson[2]

Faculty of Science and Engineering, University of Nottingham Ningbo China,
Faculty of Engineering, University of Nottingham UK
[*]email: tianlun.yang@nottingham.edu.cn
[*]email: Georgios.Kapogiannis@nottingham.edu.cn

Abstract

The lack of coordination in design practice is the cause of many problems in design business operation, and possible failure or delay in project delivery. The role of design manager is becoming important in design practice because of the necessity to manage complex design information. Level of Development (LOD) has been introduced to guide development of the BIM model and to help the control of information in building projects. This paper focuses on design companies in China with the aim of finding which features of LOD 350 will increase design coordination, enhancing design performance and improving design business operation. The paper also finds that increasing coordination between the design management team and the business management team can increase the efficiency of communication.

Key words: Design management, LOD 350, Design Business Operation

1. Problems and Introduction

Research shows that lack of coordination challenges the design operation process (Deutsch, 2011). Inefficient coordination in design practices is a common problem, and this lack of coordination causes numerous difficulties in building projects, such as delay in design, repetition of the same tasks and errors in design (Levy, 2012). This lead directly or indirectly to an increase of cost in design, for example, increasing utility bills and increasing employee working time. Therefore, it is very necessary to study the optimization of the design process in design practices, despite the existence of Building Information Modelling (BIM). Research has shown that BIM could help Small Medium Enterprises (SMEs) in their Returns on Investment (ROI) but this is not going to be the panacea (Kapogiannis, 2018), so there is opportunity to explore how to improve the design process through digital construction.

Building design consists of three phases: Schematic Design, Design Development and Construction Documents (Uniformat II, 1999). Following the design stage, there is requirement to submit construction documents in both graphical and non-graphical formats (ISO 19650, 2018). Different levels of development (LOD) are found in each phase of BIM models (See Figure 1) and can help to avoid BIM models containing too much information (Holzer, 2015). Research has found that LOD aims to create collaborative cultures for people, processes and technology (Kapogiannis, 2018).

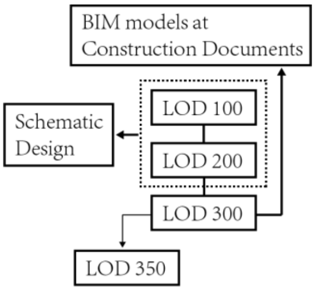


Figure 2 Level of Development (By Authors)

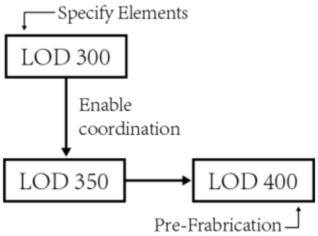


Figure 1 Role of Different LOD

This LOD specification (2018 Version) argued that LOD should evolve with project development (See Figure 2), with each LOD contributing to the construction project. Although LOD 300 has specified elements in the BIM model, coordination of the elements is not well addressed. LOD 350 aims to establish a relationship between model elements to improve design documentation, which will help design managers to improve design information coordination.

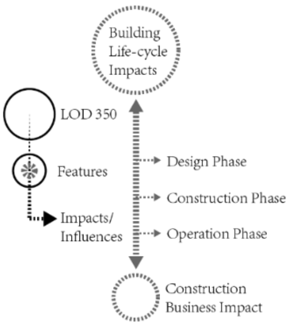


Figure 3 Role of LOD 350 (By Authors)

The quality of design management impacts on construction and facility management (Lou et al, 2019). It could be argued that lack of precise data could lead to inefficient process, despite the use of Common Data Environment (CDE), BIM software, Networks etc. The precision of a good model, according to ISO19650, is strongly linked to precise data: generic, approximate, accurate, and actual. With current LOD 350 specifications, it remains unclear why and how this level of detail will impact design practice and design business operation; therefore, this paper will investigate those features of LOD 350 (See Figure 3), and study how these features can improve working coordination in design companies. Due to length constraints, this paper will not validate the results.

2. Research Methodologies

The research is aiming to investigate and identify features of LOD 350 that could potentially improve the operation process of design practices by using secondary data and systematic review analysis. The literature review looked at fifteen fields relating to Architecture, Engineering and Construction (AEC) Industries. These papers comprehensively cover most aspects relating to construction projects and can be categorized into three parts: Design, Technologies and Business. The design element is primary in finding efficient design management solutions; the technologies element will find how to use advanced technologies to improve design management; and the business element will find business operation strategies under BIM implementations.

This paper reviews literature in current related technologies to explore advanced solutions, then finds what design of business operation is required. Literature review of the technology element finds solutions to link the design practice and business operation. Based on literature reviews, the research finds three fields in the design stage which highlight the importance of LOD: Design Planning, Sustainable Design and Quantity Survey. Also, two elements of business have accentuated LOD: BIM management and Business Interoperation.

Table 1 Major Reference Materials and Documents.

	British Standard	**ISO Standard**	**US standard**
Objects Classification	UniClass	ISO 12006-2:2015	UniFormat II/CSI UniFormat
			OmniClass
Process Guide	BS EN ISO 19650-1:2018		US National BIM Standard Version 3
	BS EN ISO 19650-2:2018		

COBie	BS 1192-4:2014		
LOD Specifications	BIM Forum LOD Specification 2018 version (Updated Annually)		
	Major Reference Materials		
BOOKS	BIM Handbook, 2nd Edition		
	Managing the Building Design Process, 2nd Edition		
	Building Design Management		

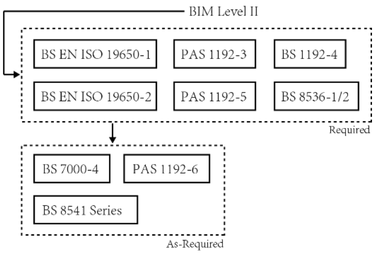


Figure 4 BIM Standards

Findings are mainly based on secondary data published by world recognized organizations such as NIBS, BSI and ISO (See Table 1), as well as on a series of standards in BIM Level II implementation strategies as listed by BreAcademy (2019) in their training in Hong Kong (See Figure 4). Other reference materials include relevant books, journals and conference papers. The results of this paper have not been validated, and further research will be conducted.

3. Finding results

Problems occur during the information model design operation process when different levels impact on decision making, work collaboration, business operation and operational management (Deutsch, 2011). The paper finds that features of LOD 350 will improve design practice and impact to design companies' business operation, although there is a gap in design collaboration across different disciplines due to inefficient communications. The focus, therefore, is on Building Design Management, Building Information Modelling (BIM) and Level of Development (LOD) in the Chinese building design market, with the aim of finding solutions to make improvement.

3.1 Building Design Management and BIM

Design practice needs IT management to improve project coordination and collaboration (Emmitt & Ruikar, 2013). Design management needs efficient information and communication flow, not only within the design team but also with clients and external specialists (Tunstall, 2006). BIM is a methodology to increase collaboration in design practice for improving building project development (Eastman et al. 2011). Emmitt and Ruikar (2013) argued that BIM is a solution to make a single model for communication and coordination and, as a new working process, highlights the role of design managers with efficient knowledge and technology management.

Gray and Hughes (2012) argued that the efficiency of communication needs to be understood and well addressed at different levels across design practice. Prior to the schematic design stage, a well-organized project brief is important. The design brief is the start of design information production, and a brief list of project needs helps designers to develop the building concept (Gray and Hughes, 2012). Farr (1965) pointed out the role of design management is finding suitable people to successfully accomplish design tasks on schedule. UK BIM level II regulates how project information needs to be managed, first with information requirements, leading to the information model. According to ISO 19650-1 (2018), Information requirements consist of Organizational Information Requirement (OIR), Project Information Requirement (PIR) and Asset Information Requirement (AIR), while information models consist of Project Information Model (PIM) and Asset Information Model (AIM).

AIM is the result of compiling building property information for construction management and PIM is built for assisting AIM in project management through building detailed information (ISO 19650-1, 2018). This paper finds these information requirements can address better information management. The design process needs efficient information coordination at each level for making design performance effective (Tunstall, 2006). Clear information requirements can guide each design phase to satisfy the perspectives of owners, users and societies (ISO 19650-1, 2018). The design manager can use these information requirements as tools to link the design team and clients to establish efficient communications. Design needs management due to the complexity of building projects, and the role of the design manager is very important (Eynon, 2013). Efficient communication with clients will increase design performance (Gray & Hughes, 2012).

Since clients are not always experienced in building projects, the design manager acts as a bridge to link design teams and clients, requesting information and informing updates. A building design project is a multi-disciplined collaborative process including the participation of architects, structural engineers, system engineers and sub-contracted specialists (Tunstall, 2006). The paper finds that in order to deliver the design on schedule, each discipline needs a lead designer for quality control and a design manager for information coordination. Gray and Hughes (2012) argued that the participation of clients will decrease after the project brief. However, this paper finds that clients still need to be involved in the project to inform on updates (eg. budget change), thus, involvement among Design Team, Design Manager and Client are equally important.

Research shows that the quality and efficiency of design management impacts on the construction business (Bryde, 2008). Although the design business is not as complex as the construction business, it is important and is depends on the quality of design management. BIM provides a solution that enables design collaboration through information interoperation and management, which aims to increase design efficiency and enhance project performance (Eastman et al. 2011). This paper has found that LOD specifications provide information guidelines for the design manager to control and organize design development. It is important that design management should efficiently coordinate those design tasks and people working on tasks through choosing the appropriate technology tools.

It is concluded that the building design project is a highly collaborative processes that requires involvement and efficient coordination and management between the Design Team, Design Manager and Clients. BIM enables the design manager to efficiently establish coordination through disciplines. Design management needs to organize both human resources and design tasks, adopting information requirements through the information delivery process, ensuring that those working on the design project have the correct task information and produce the correct documents. The design business operation is depending on the performance of the design practice, satisfaction of clients and time-consuming efficiency. Design companies can improve business operation through improving building design management by adopting advanced skills.

3.2 Features in Level of Detail 350 in BIM

LOD specification is updated by the BIM forum annually. Elements in LOD are referenced upon CSI Uniformat (2010) and OmniClass (2019) Table 21 (See Figure 5). Therefore, these two documents are the main secondary sources for studying object classifications in this paper. UniFormat (2010) is created for classifying built elements through the project lifecycle, and OmniClass (2019) is for making a standard system for classifying construction-related information in the United States. UniClass has been introduced in the United Kingdom with the same purpose. These three documents categorize elements in design practice.

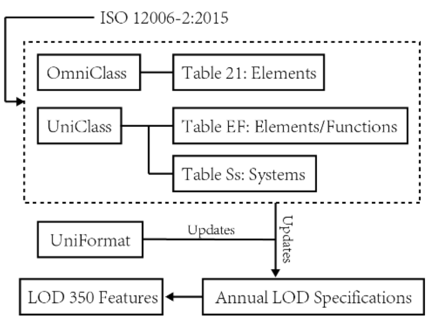


Figure 5 LOD 350 Elements Sources

Dividing problems into manageable, small pieces can help design managers to better coordinate the project and thus make design companies more successful (Farr, 1965). Building Information Modelling (BIM) can increase integrated design delivery (Deutsch, 2011), but this paper finds that there is still a need for specific solutions to efficiently accomplish design tasks. LOD provides design practice guidance in the information accumulation during different phases and contributes to BIM models (Ibrahim & Hamzeh, 2016). Different LOD levels can contribute to each project stage, enabling an elaborate building process and efficiently assessing building performance (Lattifi et al, 2015). This paper finds LOD 350 features can help the design manager to coordinate design information more efficiently

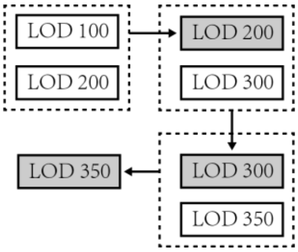


Figure 6 LOD Relations

Each level includes previous LOD information (BIMforum, 2018), and features from previous levels are inherited by the next level (See Figure 6). This paper finds element properties in different LODs are defined differently for the accuracy of elements. Furthermore, according to the research, high levels of LOD enable the design manager to assess design performance, for example, Honic, Kovacic and Rechberger (2019) argued that Material-passport based on BIM contains required information during the design process and improves optimization.

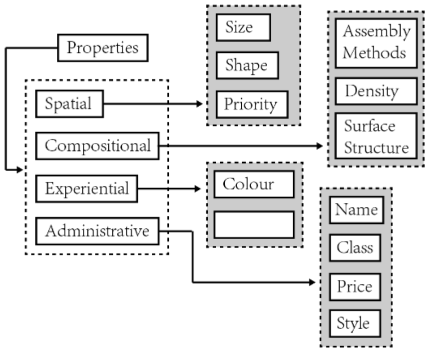


Figure 7 LOD Properties

This paper finds that features of LOD 350 allow the design manager to clearly assign design tasks. The increase of collaboration contributes to project design performance (Aguiar, Vonk & Kamp, 2019), and this leads to improvement in the design business operation. Element properties (See Figure 7) consist of Spatial, Compositional, Experimental and Administrative (ISO 12006, 2015). Features of LOD 350 have the potential to impact the design lifecycle; for example, Abou-Ibrahim and Hamzeh (2016) have introduced the concept of LOD matrix in lean design management.

Information needs to be managed during the project delivery process, and this information has been categorized into Asset Information Management, Project Information Management and Task Information Management (ISO 19650-1, 2018). This paper finds design management must combine features of LOD 350 and information management. Properties contained in LOD 350 fall into two categories: functional and non-functional (ISO 12006-2, 2015). Functional properties need to be managed under Task Information Management while non-functional properties need to be managed by Project Information Management, according to the findings of this paper. The design manager must manage all information relating to the design process in order to improve design efficiency.

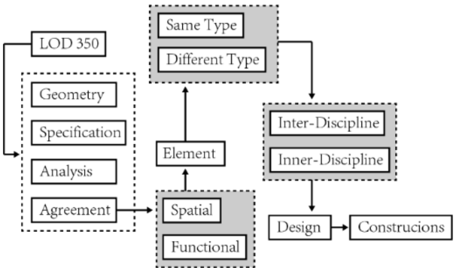


Figure 8 LOD 350 Characteristics

The paper finds interactions between elements consisting of both inner discipline and inter discipline (See Figure 8). Ganiyu, Egbu and Cidik (2018) argued that knowledge management is important during BIM implementation - hence, building design management should organize the existing knowledge in information management. The researchers find that the extent to which 350 level will impact design business operation is unclear and requires further research.

It is concluded that LOD 350 can improve design management in Task Organization, Discipline Collaboration and Information Coordination. LOD 350 features will improve the design practice, according to the findings of this paper, because they enable design managers to better control, assess and evaluate design development. Adopting a high level of detail such as LOD 350 can provide the design team with an efficient solution for organizing design information, avoiding missing data and increasing design qualities through the management of both inner and inter disciplines. This research has found that adopting technologies (eg. BIM) and improving design management will enhance design performance, and improved design performance will make the design business operation more successful.

3.3 Business Operation of Design Practice

Many Chinese design companies have multi disciplines, which include architecture, structure engineering and system engineering, and they will sub-contract third part specialists to take special designs (eg. glass curtain walls). Expenditure needs to be considered to maintain companies' business operation, for example, the salaries of employees, utilities bills and transportation fees. This paper finds that employee salaries and printing of design documents are the highest cost in the design business operation. Experienced architects and engineers demand high salaries, and high-quality colour printing is expensive. Deutsch (2011) argued that the adoption of advanced management and technologies, and transforming the environment, is not easy. However, there is a realization that BIM will improve information management, for example, Zandieh, Kani and Hessari (2016) argued that an integrated model is important for cooperation between disciplines because the design process is very complex. Kapogiannis (2018) has proved digitalization can improve those operation performances in Small to Medium Enterprises. The quality of model is significant for BIM implementation because this will affect functional purposes in further management (Reddy, 2012) This paper finds that advanced management strategies such as adopting LOD 350 will enhance business performance

Design companies in China are mostly functional organizations. Functional organizations are efficient in management but might cause conflicts between functions (Schaufelberger, 2009). First is the board of director, then the president (normally in charge of technical management). The general manager is responsible for managing internal affairs (eg. salaries, travel expenditures). Each discipline has a lead designer (also known as chief engineer) who is responsible for controlling design qualities. The existence of a design manager is not new, but is important for design coordination nowadays (Eynon, 2013). Porier, Forgues and French (2014) argued that if the Architecture, Engineering and Construction (AEC) industry increased interoperability, the BIM process would progress more efficiently. Schaufelberger (2009) discussed what each management process in an organization should focus on to improve business operation. Eastman et al (2011) argued that BIM will transform the design practice and Deutsch (2011) argued that making an impact on society is important before BIM is widely adopted. This research finds that each administrative position should participate in the design business operation to achieve business success. Eynon (2013) argued that design managers are responsible for the management of risk, human capital and information delivery in design companies. Tunstall (2006) argued that design documents should transfer design ideas in ways that would enable construction. This paper suggests design companies need efficient strategies to help design management, and enable design delivered on schedule and of high quality.

In conclusion, improving management, both in a company's organization and in the design practice will help the design business operation because the business's income is from client payments. Design companies need innovative management strategies to improve their organization management (eg. BIM) and adopt advanced technologies to enhance their design performance (eg. digitalization). Since the design practice requires input involving multiple disciplines, it is important that design managers can coordinate the design practice, manage information flow and delivery, and avoid unnecessary errors. The more efficient the completion of a project, the more resources can be put into other projects, thus leading to greater profits and a successful business operation.

4. Discussion

This research is aiming to improve design information coordination and to improve design business operation. Findings from Design Management, LOD 350 and Design Business Operations indicate that LOD 350 features will impact on the design business. It is found that poor information coordination during process and delivery is caused by a lack of clear strategies. Building designs need a design manager to accurately control the flow of information, establish communication with clients and avoid errors which delay design delivery. This paper finds each LOD 350 features will contribute to the design business, thus, both design and business managers can reference these features to improve management. Building projects are increasingly reliant on information management; Ademci and Gundes (2018) argued that projects in modern society have increased in complexity and hence there is an increased demand for integrated BIM models in project operations. Through research, this paper finds that LOD 350 could enhance design business performance due to the interactive character of its elements.

Table 2 Impacts of Non-Functional LOD 350 Properties to Design Practice

<table>
<tr><th rowspan="2"></th><th rowspan="2" colspan="2"></th><th colspan="2">Design Management</th><th colspan="2">Design Team</th><th rowspan="2">Business Management</th></tr>
<tr><th>Design Manager</th><th>Lead Designers</th><th>Architects</th><th>Engineers</th></tr>
<tr><td rowspan="10">According to ISO 12006-2:2015(E)</td><td rowspan="4">Administrative</td><td>Name</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Style</td><td></td><td></td><td>Yes</td><td></td><td></td></tr>
<tr><td>Class</td><td>Yes</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Price</td><td>Yes</td><td>Yes</td><td></td><td></td><td>Yes</td></tr>
<tr><td rowspan="2">Spatial</td><td>Shape</td><td></td><td></td><td>Yes</td><td></td><td></td></tr>
<tr><td>Size</td><td></td><td></td><td>Yes</td><td></td><td></td></tr>
<tr><td rowspan="3">Compositional</td><td>Weight</td><td></td><td></td><td></td><td>Yes</td><td></td></tr>
<tr><td>Density</td><td></td><td></td><td></td><td>Yes</td><td></td></tr>
<tr><td>Surface structure</td><td></td><td></td><td>Yes</td><td></td><td></td></tr>
</table>

Gray and Hughes (2012) found that business operation in design companies is organized into Design Management and Business Management. Design Management comprises a design manager and design team, while each discipline in the design team has a lead designer. The lead designer is responsible for design quality control and the design manager is responsible for information coordination, according to RIBA. The major inputs in the design business are human resources (eg. architects, engineers, specialists) and capital resources (eg. computers, printers, projectors), thus, business managers are responsible for eliminating waste, which compliments Lean Construction (Koskela, 2018, et, al). This research finds that each feature of LOD 350 will impact on each role in the design business (See Table 2). The design business can be divided into design management, design team and business operation. Architects and Engineers are two of the most important roles in the design team, each with different responsibilities. This research finds that there are three categories of LOD 350 features which contribute to design management: Administrative, Spatial and Compositional. Despite this, only two features can be found that impact on the design business operation; further research will be carried out to explore if other features will contribute to business performance.

This research also finds that the functional properties of LOD 350 help design managers to manage design tasks and control design information. Lead designers from each discipline can also benefit from these properties. Project design consists of different stages, and the role of different management positions will focus on different areas (Gray and Hughes, 2012). For example, business managers will focus on the project brief and design delivery in order to promote business. The lead designer focuses on project development and construction documents in order to make the design suitable for construction and operation (Emmitt and Ruikar, 2013). The design manager needs to focus on an entire stage to ensure that information is delivered from stage to stage in order for the design to be complete, on schedule and of good quality (Tunstall, 2006). Those features found in the table can be categorized into qualitative and quantitative characteristics, and this paper finds that quantitative features can be combined with qualitative ones. Thus, the features can be integrated to impact both the design practice and the design business.

It is concluded that, so far, this paper finds features of LOD 350 can help design companies in two aspects: Design Management and Business Management. Improved design management can enhance design performance which can have a positive social impact (eg. environmental, commercial), while improved business operation will raise company profit that can help companies' long-term development (eg. hire more skilled people, purchase more advanced equipment). This research finds that the impact of LOD 350 on business operation starts in programming and planning because these stages prepare the design project. Features of LOD 350 enable information flow in a coordinated way during schematic design, design development and construction drawings, which solves the research problem of this paper. There are still many other reasons for inefficiency in design coordination, thus, more research will need to be done.

5. Conclusions

This paper has found solutions to solve problems relating to inefficiency in design coordination. According to the findings, features of LOD 350 will help design managers to improve information process and delivery during design practice. Furthermore, it is found that LOD 350 will not only help design managers, but also business managers in design companies to enhance business operation through efficiently managing capital inputs. Inefficient coordination in design practice can be solved by improving information and technology management as this allocates resources (both human resource and capital assets) appropriately, thus leading to improved success in design business operation.

To summarize, features of LOD 350 will enhance building design performance and impact on design business operation. The results have not been validated due to the limits of this research; thus, further research will focus on validating those findings. This paper is a partial study from a PhD topic, so more in-depth research will be conducted in the future. The methods used to validate these results will be case studies, questionnaires and surveys. The contribution to knowledge of this topic is to find solutions to improve design coordination and enhance the performance of design business through combining design management, levels of development and technological innovations.

Acknowledgements

Sincere thanks to Zhejiang Jingwei Engineering Design Co. Ltd and Ningbo Chuang-An Engineering Management Co. Ltd for funding this research.

References

Abualdenien, J., & Borrmann, A. (2018, September). Multi-LOD models for describing uncertainty and checking requirements in different design stages. In *eWork and eBusiness in Architecture, Engineering and Construction, Proceedings of the 12th European Conference on Product and Process Modeling (ECPPM 2018).*

Ademci, E., & Gundes, S., (2018, November). Review of Studies on BIM adoption in AEC Industry. In Architecture, Engineering and Construction, Proceedings of 5th International Project and Construction Management Conference (IPCMC 2018).

Aguiar, A., Vonk, R., & Kamp, F. (2019). BIM and Circular Design. Earth and Environmental Science, 10.1088

British Standards Institution. (2014). Collaborative production of Information Part 4: Fulfilling employer's information exchange requirements using COBie-Code of practice (BS 1192-4: 2014).

BIMforum. (2018). Level of Development (LOD) Specification Part I & Commentary for Building Information Models and Data.

BSI. (2019). Organization and digitization of information about building and civil engineering works, including building information modelling (BIM) – Information management using building information modelling, Part 1: Concepts and Principles (BS EN ISO 19650-1:2018). London: British Standards Institution.

BSI. (2019). Organization and Digitization of Information about building and civil engineering works, including building information modelling (BIM) – Information management using building information modelling, part 2: Delivery phase of the asset (BS EN ISO 19650-2:2018). London: British Standards Institution.

Charette, R.P., & Marshall, H.E. (1999). Uniformat II Element Classification for Building Specifications, Cost Estimating and Cost Analysis (NISTIR 6389). Montreal: National Institute of Standards and Technology

CSI, (2010). Uniformat: A Uniform Classification of Construction System and Assemblies. Toronto: Construction Specification Institute.

Deutsch, R. (2011). BIM and Integrated Design: Strategies for Architectural Practice. Hoboken: Wiley.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). BIM handbook: A guide to Building Information Modelling for Owners, Designers, Engineers and Contractors. (2nd ed.). Hoboken: Wiley.

Emmitt, S., & Ruikar, K. (2013). Collaborative Design Management. Abingdon: Routledge.

Eynon, J. (2013). The Design Manager's Handbook. Chichester: Wiley-Blackwell.

Gray, C., & Hughes, W. (2012). Building Design Management. Abingdon: Routledge.

Ganiyu, S.A., Egbu, C.O., & Cidik, M.S.M. (2018, December). Knowledge Management and BIM practice. In Architecture, Engineering and Construction, Proceedings of 1ST Psycon International Conference 2018.

Holzer, D. (2015) The BIM manager's Handbook ePart 1. Wiley: Chichester

Honic, M., Kovacic, I., & Rechberger, H. (2019). Concept for a BIM-based Material Passport for Buildings. Earth and Environmental Science, 225 012073

ISO. (2015). Building Construction-Organization of Information about Construction Works-Part 2: Framework for Classification (ISO 12006-2:2015). Geneva: International Standard Organization.

Ibrahim, H.A., & Hamzeh, F. (2016). Enabling Lean Design Management: An LOD Based Framework. Lean Construction Journal 2016, pp 12-24.

Kapogiannis, G., & Sherratt, F. (2018). Impact of integrated collaborative technologies to form a collaborative culture in construction projects. Built Environment Project and Asset Management, 10.1108

Koskela, J. L., Ferrantelli, A., Niiranen, J., & Pikas, E. (2018). Epistemological Explanation of Lean Construction. Journal of Construction Engineering and Management 2018, 10.1061

Levy, F. (2012). BIM in Small-Scale Sustainable design. Hoboken: Wiley.

Latiffi, A.A., Brahim, J., Mohd, S., & Fathi, M.S. (2015). Building Information Modeling (BIM): Exploring Level of Development (LOD) in Construction Projects. Applied Mechanics and Materials, 10.4028

Lou, T., He, B., Zhang, B., & Duan, Z. (2019). Research and Application of BIM Project Group Management. Earth and Environment Science, 218-012056

NIBS. (2015). National BIM standard-United States Version 3: Transforming the Building Supply Chain Through Open and Interpretable Information Exchange. Washington D.C: National Institute of Building Science

Poirier, E.A., Forgues, D., & French, S.S. (2014, May). Dimensions of Interoperability in the AEC industry. In Architecture, Engineering and Construction, Proceedings of Construction Research Congress 2014

Pruskova, K. & Kaiser, J. (2019). Implementation of BIM technologies into the Design Process Using the Scheme of BIM execution plan. Material Science and Engineering, 471 022019

Reddy, K.P. (2012). BIM for Building Owners and Developers: Making a Business Case for using BIM on Projects. Hoboken: Wiley.

Schaufelberger, J. (2009). Construction Business management. Columbus: Pearson.

Tunstall, G. (2006). Managing the Building Design Process. (2nd ed.). Oxford: Butterworth-Heinemann.

Vitasek, S., & Zak, J. (2018, September). BIM for Cost Estimation. In Architecture, Engineering and Construction, Proceedings of 3rd International Conference on Engineering Science and Technologies, Kosice.

Zandieh, M., Kani, I.M., & Hessari, P., & Kirkegaard, P.H. (2016). Adoption of BIM system in the AEC industry. Ponte, 10.21506

BIM-based machine learning engine for prediction of building energy consumption

Sisi Bie[1*] and Haijiang LI[1]
[1]BIM for Smart Engineering Centre, Cardiff University, Cardiff, Wales, UK
* email: Bies@cardiff.ac.uk

Abstract

Buildings consume a large amount of energy; it is therefore important to find a better way to manage building energy performance more effectively. The recent developments in data science and machine learning show a good potential to leverage the different sources of data to predict energy consumption. This paper reviews the current research in these areas and proposes a BIM (Building Information Modelling) based approach to provide data and information to train the relevant machine learning (ML) engine. The method has been demonstrated with a daylight illuminance prediction analysis. The presented preliminary result can potentially lead to a more generic tool, where rich data and information embedded in BIM models can be utilized for better decision making.

Keywords: BIM (Building Information Modelling), ML (Machine Learning), Building energy consumption.

1. Introduction

Building energy consumption takes a large part of the energy, for example it reported in Europe, the building energy use represents 40% of total energy consumption (Bull, Chang, & Fleming, 2012). The prediction of building energy consumption is therefore important to achieve energy conservation and reduce the environmental impact. However, there is lacing a better way to manage building energy performance more effectively.

BIM has been more widely used in the construction industry than ever before. More and more BIM models are accumulated for various industry organisations. The data embedded in BIM models include geometry, materials, energy, safety. Most of them are simply archived with little effort to find use out of it. The data, information and knowledge embedded in those BIM models can be leveraged to conclude knowledge to benefit the organisations, but how to leverage the data to get benefits remains unclear. The recent advances in machine learning could potentially help resolve this issue, e.g. machine learning methods have been used to clash detection and so on (Hu & Castro-Lacouture, 2018). artificial intelligence method could be very quick as it is based on 'searching' for pre-trained solutions. Also, comparing to the traditional way of building energy analysis, the values from the ML engine are more representative of actual building performance than simulation values (Chen, 2019). The training data sources used for ML can come from real historical data and simulation-based mocked data. Traditional building energy simulation during the design stage is time-consuming and often comes with biased errors. The BIM way of working is to integrate energy simulation data into BIM models; hence it can provide comprehensive life cycle data sets, which can create an automated energy controller in the lifecycle of a building. Therefore, the BIM can provide data to ML for solving the specific problems.

Usage of artificial light takes a large part of energy consumption in a building. Artificial lighting is controlled by the prediction of daylight illumination to reduce electric consumption. The traditional method is to place sensors to the reference point to collect data all the time. However, the sensor is an expenditure and can be easily removed from the reference point when collecting the daylight illuminance data. Also, the simulation model by the software can simulate the operation status of this building, but it needs to rebuild the model every time. Hence it cannot realise the real-time illuminance prediction engine.

This paper therefore proposes a BIM (Building Information Modelling) based approach to provide data and information to train the relevant machine learning (ML) engine, which is further used for real-time illuminance prediction. The overall contents include 4 sections, (1) Introduction; (2) Literature Review; (3) Development and Implementation; (4) Conclusion. The Literature Review covers BIM supporting building energy analysis, ML for building energy consumption and using BIM and ML supporting construction industry applications. the authors propose and develop a prototype of BIM-based ML engine and tested via a simple case study. Future work has been discussed at the end of the paper.

2. Literature Review

In this section, published articles are reviewed from major databases, including ScienceDirect, Scopus, Google Scholar. The searching dates are from 2010 to July 2019. Keywords used for searching were: 1) "Building information modelling" and "Building Energy" and "data"; 2) "Machine learning" and "Building Energy"; 3) "Building information modelling" and "Machine learning". The inclusion criteria are: 1) The studies published in English or in other languages with English abstracts; 2) Only search research articles; 3) All the keywords should be included. The exclusion criteria were: 1) Uncorrelated 2) Outdated before 2010. The result has been illustrated in three fields: 1) BIM applied to energy simulation 2) ML for building energy consumption;3) ML applied with BIM. It can be seen form figure 1 that the number of studies on ML for building energy consumption area are significantly increased over years, which can reflect the truth that energy is a big concern in the word. BIM-based building energy analysis has a moderate growth, comparing the ML for building energy analysis, the quantity of studies on this area is less. The findings are limited in BIM and ML combined area.

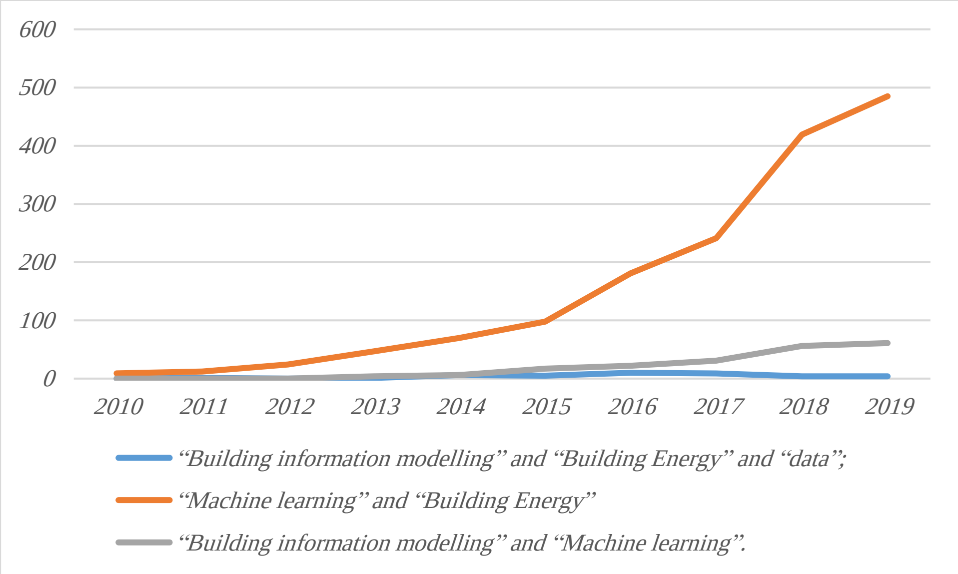


Figure 1: The Quantity of Publications in Different Domain

2.1 BIM supporting building energy analysis

BIM is a method monitoring the whole life cycle of a construction (Eleftheriadis, Mumovic, & Greening, 2017). BIM captures multi-dimensional CAD information (Eadie, Browne, Odeyinka, McKeown, & McNiff, 2013). This digital revolution boosts the development of the AEC industry. The data can be easily accumulated and collected by the integration of BIM models. The concept of BIM is referred by the Krygiel et al. (2008) to an integrated database which stored all parametric and interconnected information of the entire building, and design documents. It will be reflected instantly throughout the rest of the project in all views if there are any changes to an object in the model. Additionally, as more systems have been added to buildings, the more energy is demanded to operate them.

There are many contributions of BIM in building energy domain, such as automation of energy modelling, enhancing the existing libraries, and storing and organizing the building data (Kamel & Memari, 2019). The main format of the BIM file is gbXML and IFC, which are generated from the BIM tool such as Revit. The research in 2015 developed a ModelicaBIM library for BIM-based building energy simulation (Kim, Jeong, Clayton, Haberl, & Yan, 2015). The ModelicaBIM library was used to investigate the system interface between BIM and energy simulation. This system interface can semi-automatically translate the building models in BIM to building energy models.

2.2 ML supporting energy consumption prediction

Recently, the ML method is used in many areas, such as the prediction of building energy consumption. There are hundreds of studies on this domain. Aimed at reaching the goal of energy-saving and reduction of environmental influence, it is vital to predict the building energy consumption to enhance the performance of the building.

For example, in 2012, a review study summarized that there are four main categories of methods in building energy prediction: The engineering methods, Statistical methods regression, AI(Artificial intelligence) methods, Grey model (Zhao & Magoulès, 2012). The AI method mainly includes artificial neural networks, support vector machines, decision tree etc. From the review study in 2018, a summary of energy consumption prediction models was proposed from four aspects: scoping data properties, algorithms, and performance (Amasyali & El-Gohary, 2018).

The artificial neural network (ANN) is the popular AI method which was used in building energy management (Bilal et al., 2016). This method is performed well and effective in solving non-linear and complex problems. The input data is the most important factor in ANNs method. Because of the noise of raw data, the data pre-processing technologies are developed by many researchers. In 2018, research conducted the machine learning method to forecast the usage of energy in a building (Dan & Phuc, 2018). Their dataset comes from historical data and the building design parameters.

2.3 The BIM-based ML development

BIM's method is top-down modelling of information while machine learning is a data-driven bottom-up approach that can help to identify structure and semantics in data. Hence, BIM developed the 'knowledge discovery' by providing information right out of the box. There are many studies on the application of machine learning in building design. However, there are only a few pieces of research on knowledge discovery by using the advantage of BIM model.

Many ML methods were fine-tuned used in different fields. Looking back over the last ten years, the recognition of project progress in construction sites was conducted with ML methods based on the data from photos in sites and BIM models (Golparvar-Fard, Peña-Mora and Savarese, 2012). Then an integrated framework related on coordinating sensor and BIM element was proposed by Bogen etc. (Bogen, Rashid, East, & Ross, 2013), which was aimed to comparing the running state with the scheduled state of facilities in buildings. K-means clustering and hierarchical clustering were used for classifying the resource usage according to a resolution typical of human-specified schedules. Then the experiment in 2014 used deep learning method to classify 3D models under the environment of BIM, which had a good result (Qin, Li, Gao, Yang, & Chen, 2014). In 2015, the research was focused on semi-automation and automation of collecting and dealing with various photos from infrastructure construction sites (Teizer, 2015). It used the image recognition techniques to capture, analyse and record the process of construction. Based on the previous research, a study in 2016 got a good result of 3D façade modelling and materials recognition through photo recognition for as-built building (Yang, Shi, & Wu, 2016). The next year, a basic clash detection in the construction safety domain was proposed using ML (Tixier, Hallowell, Rajagopalan, & Bowman, 2017). At the same time, based on data in the construction material library (CML) and development of BIM, a web-based platform to simplify the process of data collection was used to annotate material patches according to BIM overlays (Han & Golparvar-Fard, 2017). In 2018, an application of machine learning used for semantic enrichment BIM models has been proposed for extensive data pre-processing (Bloch & Sacks, 2018a). The paper in the same year showed that the ML method is directly applicable to space classification problems(Bloch & Sacks, 2018b). Similarity, ML technologies could distinguish the relevant and irrelevant clashes which used to enhance the quality of clash detection (Hu & Castro-Lacouture, 2018). In 2019, the researcher proved that the predicted values from ML engine are more representative of actual building performance than simulation values (Chen, 2019). At the same time, a deep convolutional neural network was used in indoor localization, which could recognise the synthetic images from 3D indoor model recognise (Acharya, Khoshelham, & Winter, 2019). A research proposed an AI method to generate proper building design according to the requirement of client, but the researcher only realised automation of a window design(Karan & Asadi, 2019). Also, NLP and unsupervised learning were used to automatically distinguish whether it is the BIM case study(Jung & Lee, 2019). According to the previous works, the main application and implication of BIM-based ML are mentioned. This cross-domain requires further research into the potential of BIM-based ML using.

3. Development and Implementation

3.1 System design

Based on the reviewed published research and research gaps, a prototype of a combination of BIM-based ML engine for building energy consumption is proposed and showed in figure 2. BIM files produced by BIM tools, such as Revit, can be input in Graphical User Interface (GUI), according to the different file format. Then, the modified file can be mapped in the energy simulation engine, such as Energyplus. After that, the simulated energy data can be fed into the ML engine, which is the most key step in this model. So many ML algorithms can be used to make building energy prediction. In addition, the output of previous steps can be stored back in the smart BIM framework for controlling the whole life cycle of buildings. A smart BIM model is then developed from original BIM models.

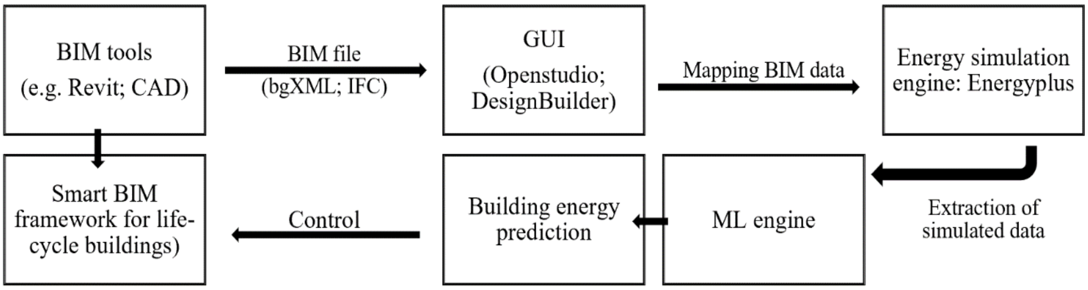


Figure 2: A prototype of BIM-based ML engine for energy consumption

3.2 Case study

The target of energy consumption contains many aspects, this case study starts from a simple target: daylight illuminance prediction. Designbuilder can easily export the idf file, which can be imported to Energyplus software directly. Energyplus here is being used for dataset simulation. Then, machine learning algorithms will be used to train the model. Once the machine learning model is trained, a real-time daylight luminance prediction can be made based on the model, given the future weather data for an existing building, which can be used to control the artificial light automatically in a building. Here are the steps in this case study.

3.2.1 Create BIM model using BIM software

A BIM model for a normal terraced house located in Cardiff was built in Designbuilder, which is shown in Figure 3. below. It is a two-layers classic single-family house in the UK. Here the living room on the ground floor has been used for daylight analysis.

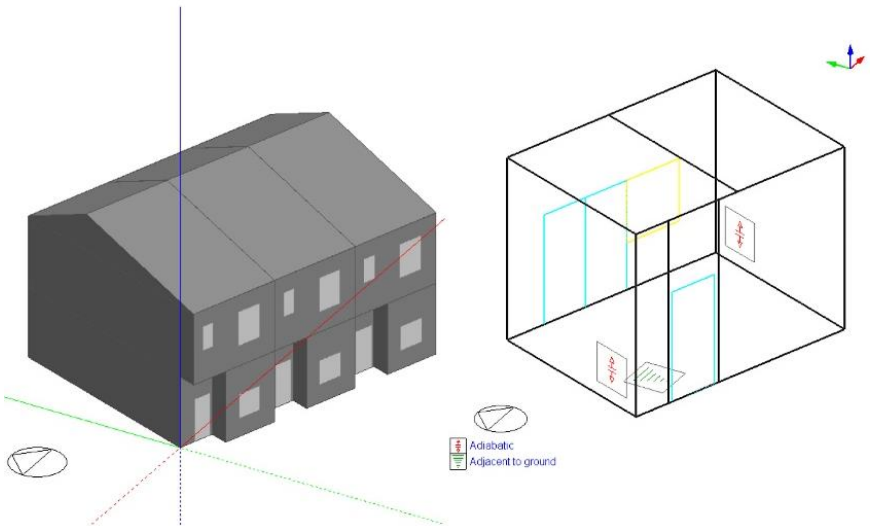


Figure 3: 1) the terraced single-family house; 2) the layout of the living room in this house.

A simulated sensor was set in the middle of the room, where the height is 0.8 meters. Then a one-year period from 1 January to 31 December was chosen to simulate. This house is located in the Cardiff area. The simulated result can be seen in figure 4. From April to October, the general lighting indicated by the blue line is reduced because of the longer daytime (yellow line) than other time, because of the typical UK weather format.

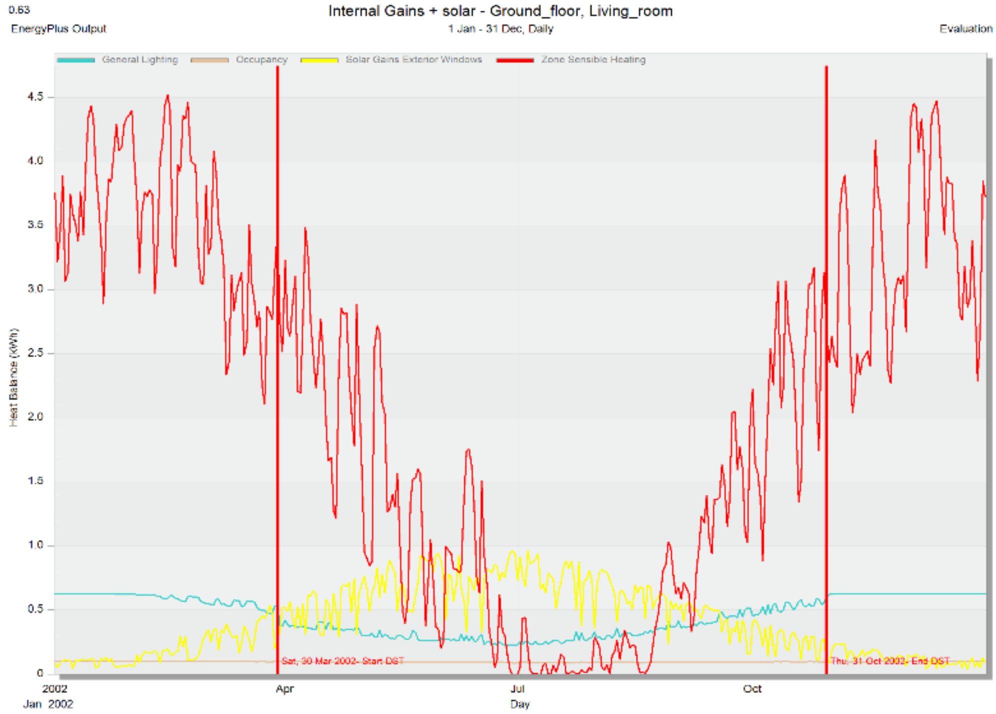


Figure 4: The visible one-year simulated result in Designbuilder.

3.2.2 Extract energy data from a BIM model

According to Energyplus input and output reference document, there are 10 output variables, that can be modified: hour of the day, outdoor Air Drybulb Temperature [C], Site Outdoor Air Humidity Ratio [kgWater/kgDryAir], Site Wind Speed [m/s], Site Diffuse Solar Radiation Rate per Area [W/m2], Site Direct Solar Radiation Rate per Area [W/m2], Site Solar Azimuth Angle [deg], Site Solar Altitude Angle [deg], Zone Windows Total Transmitted Solar Radiation Rate [W], Daylighting Reference Point 1 Illuminance [lux]. The output dataset of Energyplus can be shown in an xlsx or csv format file in excel, some of which are shown in figure 5 below.

	A	B	C	D	E	F	G	H	I	J
1	Date/Time	Environment:Site Outdoor Air Drybulb Temperature [C](Hourly)	Environment:Site Outdoor Air Humidity Ratio [kgWater/kgDryAir](Hourly)	Environment:Site Wind Speed [m/s](Hourly)	Environment:Site Diffuse Solar Radiation Rate per Area [W/m2](Hourly)	Environment:Site Direct Solar Radiation Rate per Area [W/m2](Hourly)	Environment:Site Solar Azimuth Angle [deg](Hourly)	Environment:Site Solar Altitude Angle [deg](Hourly)	3145:Zone Windows Total Transmitted Solar Radiation Rate [W](Hourly)	3145:Daylighting Reference Point 1 Illuminance [lux](Hourly)
2	01/01 01:00:00	8.525	0.006649	5.675	0	0	13.73314	-60.926	0	0
3	01/01 02:00:00	8.325	0.006496	5	0	0	39.31949	-56.7506	0	0
4	01/01 03:00:00	8.55	0.006536	5.8	0	0	59.28305	-49.6835	0	0
5	01/01 04:00:00	8.6	0.006679	6.575	0	0	74.78922	-41.1099	0	0
6	01/01 05:00:00	8.825	0.00705	8.2	0	0	87.64132	-31.9081	0	0
7	01/01 06:00:00	9.5	0.007469	6.45	0	0	99.14265	-22.6113	0	0
8	01/01 07:00:00	10.075	0.007538	5.25	0	0	110.1509	-13.5984	0	0
9	01/01 08:00:00	10.125	0.007731	4.35	0	0	121.2574	-5.20262	0	0
10	01/01 09:00:00	10.625	0.007902	4.475	14.25	11	132.8861	2.23384	2.509658	48.87171
11	01/01 10:00:00	10.725	0.007899	4.225	52.75	90.75	145.3104	8.338182	10.02342	185.5677
12	01/01 11:00:00	10.7	0.00814	3.35	81.75	224.75	158.6091	12.72221	16.34238	242.1758
13	01/01 12:00:00	10.625	0.007939	3.1	104.75	190.75	172.6063	15.04087	19.74009	278.5615
14	01/01 13:00:00	10.675	0.007755	3.475	116	128	186.8789	15.08278	20.48618	280.4431
15	01/01 14:00:00	11.15	0.007976	5.55	87.5	57.75	200.8946	12.84392	15.04453	201.7524
16	01/01 15:00:00	11.225	0.007829	5	46	0	214.2233	8.52915	7.800996	121.1626

Figure 5: Partly show the extracted dataset in Excel form

3.2.3 ML algorithms development

According to the hourly simulated dataset from Energyplus, the 9 input variables are chosen for the ML engine, while the only target variable is daylight illuminance. The figure 6 gives a clear view of 9 input variables and one output in ML engine. From the previous review, the main machine learning algorithms such as ANN and Random Forest (RF) used here only accept the consistent data type. Hence, the time step of record instance is hourly, the time can be assigned by 1 to 8760. There are a total of 8760 instances in this dataset. Weka is a commercial ML software based on C plus language, which is friendly with engineers. This dataset in excel can be fed into Weka software for normalization and training. 66% of the dataset is for training and the remainder are for testing.

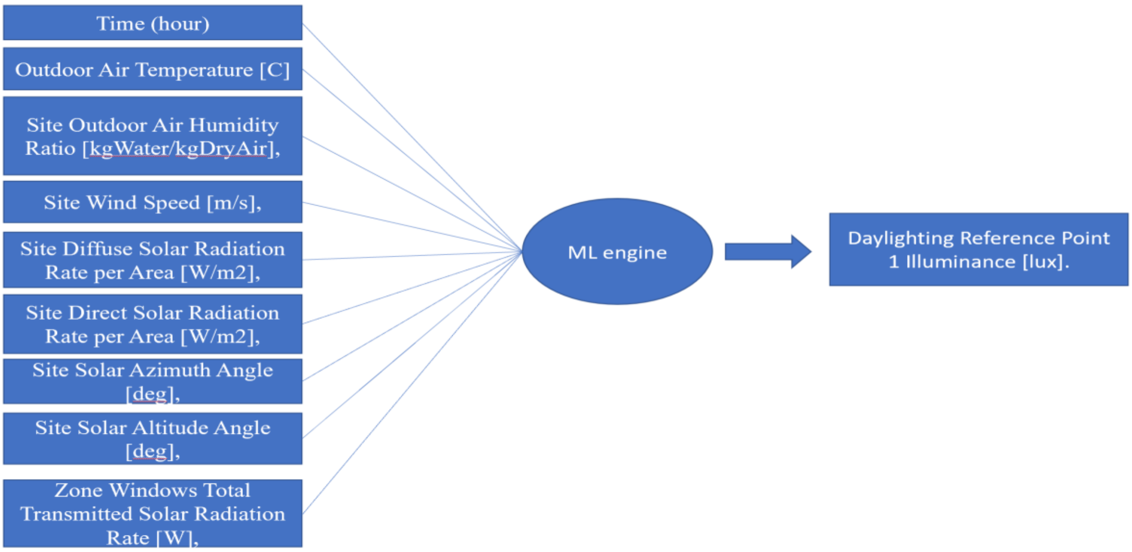


Figure 6: The input and output of machine learning engine

Multilayer Perceptron, Random Forest (RF), and Linear Regression are mainly algorithms used in this study. Multilayer Perceptron is a classic feedforward neuron network. Here the author uses one hidden layer and chooses 3,5 and 7 neurons per layer respectively. After comparing the results from different neurons per layer, the author finds that the neuron network with 5 neurons per layer performed better than other options here. Hence, the ANN built in this experiment has only one hidden layer and 5 neurons per layer. Random forest has a high degree of accuracy and the high speed of learning process. Here the bag size percent and batch size are both 100. The tree depth is unlimited here in each tree of the random forest. Linear regression is used for comparison with other two methods here. Cross-validation rank in 10 for detecting the errors. The experiment compares these three methods from five aspects: correlation coefficient, mean absolute error, root mean squared error, relative absolute error, root relative squared error. The result is illustrated in table 1. The linear regression has higher errors than others. The reason for this situation is that this dataset is highly scattered.

Table 1: The Result of Each Algorithms

	Correlation coefficient	Mean absolute error	Root mean squared error	Relative absolute error	Root relative squared error	Total Number of Instances
Multilayer Perceptron (1 hidden layer, 5 neurons per layer)	0.9948	21.6228	30.5761	9.15%	10.51%	8760
Random Forest -P 100 -I 100 -num-slots 1 -K 0 -M 1.0 -V 0.001 -S 1	0.9991	6.3013	12.5186	2.67%	4.30%	8760
Linear Regression	0.9531	52.6389	88.016	22.28%	30.26%	8760

3.2.4 Discussion

Form the result in table 1, firstly, the Correlation coefficient of these algorithms presented here nearly equals to 1. It indicates that the input variables have high Correlation with the output variables. The daylight illuminance is mainly affected by the time of day and other weather conditions, also there are other effects like surrounding buildings and trees. Secondly, there are other results in the table. 2, which include Mean absolute error, Root mean squared error, Relative absolute error, Root relative squared error. All of these errors are similar to measuring the error between real value and prediction value. The RF has obvious smaller errors than the other two algorithms, which shows a significant advantage than the other two in the regression problem for daylight illuminance prediction. Additionally, form the structure of the dataset, the number of 0 value of the daylight illuminance in the wintertime is more than in the summertime. It can reflect the weather condition in the UK, where the daytime in winter is shorter than summer. Thus, the prediction of future daylight illuminance through the weather forecast is feasible for an existing real building. It can also be used in other aspects of the energy area.

4. Conclusion

The authors presented a simple case with limited data in this study to demonstrate how to extract energy data from the BIM model to predict the real-time daylight illuminance using the ML engine in the life cycle of the building. It shows the feasibility of using the weather forecast to predict the future daylight illuminance for an existing real building. Additionally, it also presents the feasibility of deducing the implicit knowledge from BIM model. There are other effects of input variables that were not considered comprehensively, such as other shelters near the building etc. Based on the existing problem in the energy consumption filed, this engine can be extended to other aspects in the energy area. It is therefore can realize smart energy management in buildings.

References

Acharya, D., Khoshelham, K., & Winter, S. (2019). BIM-PoseNet: Indoor camera localisation using a 3D indoor model and deep learning from synthetic images. *ISPRS Journal of Photogrammetry and Remote Sensing*, *150*(March), 245–258. https://doi.org/10.1016/j.isprsjprs.2019.02.020

Amasyali, K., & El-Gohary, N. M. (2018). A review of data-driven building energy consumption prediction studies. *Renewable and Sustainable Energy Reviews*, *81*(September 2017), 1192–1205. https://doi.org/10.1016/j.rser.2017.04.095

Bilal, M., Oyedele, L. O., Qadir, J., Munir, K., Ajayi, S. O., Akinade, O. O., … Pasha, M. (2016). Big Data in the construction industry: A review of present status, opportunities, and future trends. *Advanced Engineering Informatics*, *30*(3), 500–521. https://doi.org/10.1016/j.aei.2016.07.001

Bloch, T., & Sacks, R. (2018a). Comparing machine learning and rule-based inferencing for semantic enrichment of BIM models. *Automation in Construction*, *91*(March), 256–272. https://doi.org/10.1016/j.autcon.2018.03.018

Bloch, T., & Sacks, R. (2018b). Comparing machine learning and rule-based inferencing for semantic enrichment of BIM models. *Automation in Construction*, *91*(July 2017), 256–272. https://doi.org/10.1016/j.autcon.2018.03.018

Bogen, A. C., Rashid, M., East, E. W., & Ross, J. (2013). Evaluating a data clustering approach for life-cycle facility control. *Journal of Information Technology in Construction*, *18*, 99–118.

Bull, R., Chang, N., & Fleming, P. (2012). The use of building energy certificates to reduce energy consumption in European public buildings. *Energy and Buildings*, *50*, 103–110. https://doi.org/10.1016/j.enbuild.2012.03.032

Carnot, N., Koen, V., Tissot, B., Carnot, N., Koen, V., & Tissot, B. (2016). Modelling Behaviour. *Economic Forecasting*, (buildingSMART 2014), 103–132. https://doi.org/10.1057/9780230005815_5

Chen, S. (2019). *Enhancing Validity of Green Building Information Modeling with Artificial-neural-network-supervised Learning — Taking Construction of Adaptive Building Envelope Based on Daylight Simulation as an Example*. *31*(6), 1831–1845.

Dan, T. X., & Phuc, P. N. K. (2018). Application of Machine Learning in Forecasting Energy Usage of Building Design. *Proceedings 2018 4th International Conference on Green Technology and Sustainable Development, GTSD 2018*, 53–59. https://doi.org/10.1109/GTSD.2018.8595595

Eadie, R., Browne, M., Odeyinka, H., McKeown, C., & McNiff, S. (2013). BIM implementation throughout the UK construction project lifecycle: An analysis. *Automation in Construction*, *36*, 145–151. https://doi.org/10.1016/j.autcon.2013.09.001

Eleftheriadis, S., Mumovic, D., & Greening, P. (2017). Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities. *Renewable and Sustainable Energy Reviews*, *67*, 811–825. https://doi.org/10.1016/j.rser.2016.09.028

Golparvar-Fard, M., Peña-Mora, F., & Savarese, S. (2012). Automated Progress Monitoring Using Unordered Daily Construction Photographs and IFC-Based Building Information Models. *Journal of Computing in Civil Engineering*, *29*(1), 04014025. https://doi.org/10.1061/(asce)cp.1943-5487.0000205

Han, K., & Golparvar-Fard, M. (2017). Crowdsourcing BIM-guided collection of construction material library from site photologs. *Visualization in Engineering*, *5*(1). https://doi.org/10.1186/s40327-017-0052-3

Hu, Y., & Castro-Lacouture, D. (2018). Clash Relevance Prediction Based on Machine Learning. *Journal of Computing in Civil Engineering*, *33*(2), 04018060. https://doi.org/10.1061/(asce)cp.1943-5487.0000810

Jung, N., & Lee, G. (2019). Automated classification of building information modeling (BIM) case studies by BIM use based on natural language processing (NLP) and unsupervised learning. *Advanced Engineering Informatics*, *41*(April), 100917. https://doi.org/10.1016/j.aei.2019.04.007

Kamel, E., & Memari, A. M. (2019). Review of BIM's application in energy simulation: Tools, issues, and solutions. *Automation in Construction*, *97*(October 2018), 164–180.

https://doi.org/10.1016/j.autcon.2018.11.008

Karan, E., & Asadi, S. (2019). Intelligent designer: A computational approach to automating design of windows in buildings. *Automation in Construction*, *102*(February), 160–169. https://doi.org/10.1016/j.autcon.2019.02.019

Kim, J. B., Jeong, W., Clayton, M. J., Haberl, J. S., & Yan, W. (2015). Developing a physical BIM library for building thermal energy simulation. *Automation in Construction*, *50*(C), 16–28. https://doi.org/10.1016/j.autcon.2014.10.011

Qin, F., Li, L., Gao, S., Yang, X., & Chen, X. (2014). A deep learning approach to the classification of 3D CAD models. *Journal of Zhejiang University SCIENCE C*, *15*(2), 91–106. https://doi.org/10.1631/jzus.c1300185

Teizer, J. (2015). Status quo and open challenges in vision-based sensing and tracking of temporary resources on infrastructure construction sites. *Advanced Engineering Informatics*, *29*(2), 225–238. https://doi.org/10.1016/j.aei.2015.03.006

Tixier, A. J. P., Hallowell, M. R., Rajagopalan, B., & Bowman, D. (2017). Construction Safety Clash Detection: Identifying Safety Incompatibilities among Fundamental Attributes using Data Mining. *Automation in Construction*, *74*, 39–54. https://doi.org/10.1016/j.autcon.2016.11.001

Yang, J., Shi, Z. K., & Wu, Z. Y. (2016). Towards automatic generation of as-built BIM: 3D building facade modeling and material recognition from images. *International Journal of Automation and Computing*, *13*(4), 338–349. https://doi.org/10.1007/s11633-016-0965-7

Zhao, H., & Magoulès, F. (2012). A review on the prediction of building energy consumption. *Renewable and Sustainable Energy Reviews, 16*(6), 3586–3592. https://doi.org/10.1016/j.rser.2012.02.049

From a meagre ‘testing for interoperability’ to the ‘measurement of interoperability’ in BIM

Joseph Jabin[1*], Johannes Dimyadi[2], Robert Amor[1]

[1]University of Auckland
[2]Compliance Audit Systems Limited

[*]email: jkan585@aucklanduni.ac.nz

Abstract

Current conformance tests for BIM (Building Information Modelling) data exchange standards are not reliable, as reported in the literature. It is understood that no conformance test can check for 100% error-free operation, as it is a test of the ability to exchange information rather than a measure of the quality of the information exchange. This research has investigated if the current conformance test methodology is in accordance with established measurement theories and therefore, can be used to measure the interoperability of a BIM software tool against a data exchange standard. It was found that current conformance tests do not conform to measurement theory and are not able to accurately convey the results and any limitations of the measurement to the end-user. To investigate how other domains have measured interoperability and whether any of their metrics are useful for measuring interoperability in BIM, a systematic literature review (SLR) was conducted. The SLR has gathered 28 interoperability measurement models. They were analysed in terms of established principles in the measurement theory and from that current deficiencies in the interoperability measurement for BIM were identified. Suggestions are given on upgrading the current conformance tests to be compliant with the measurement theory so that they will convey more accurate information to the end-users.

Keywords: BIM, Conformance test, Certification, Interoperability, Measurement theory

1. Introduction

Conformance tests (or compliance tests in some literature) for BIM (Building Information Modelling) are conducted by mainstream organisations like buildingSMART, Green Building Council, US National Institute of Building Sciences, etc. to determine how a BIM software tool interoperates with data exchange standards like IFC, gbXML, COBie, etc. These tests are used to certify the ability of various BIM software tools to interoperate with data exchange standards. This gives the perception that a conformance test is a de-facto process for measuring interoperability. The tests check if a native representation of BIM data in a BIM software tool can map to various objects and attributes in a data exchange standard. The result of the conformance test is a list of mapped attributes along with information on whether each attribute was successfully mapped from the native representation to that of the data exchange standard and vice versa (buildingSMART, 2019). Upon successful completion of the test, the software is awarded a certification, and the software vendor can display the appropriate logo (e.g., IFC2x3 Certified) on their promotional materials (buildingSMART, 2010). Researchers have pointed out that the certification process is not reliable as the certified software tools still have interoperability issues with the data exchange standard (Amor & Dimyadi, 2010; Kiviniemi, 2008; Lipman, Palmer, & Palacios, 2010). There are arguments that no certification scheme can guarantee completely error-free operations (Steinmann, 2018), and the certification process is a test of the ability of a software product to exchange information with the data exchange standard rather than the quality of the exchange (Lipman et al., 2010). These limitations are not conveyed through the certification logos. At the same time, the inherent data exchange issues are not aligned with end-user expectations that a certified software tool will exchange data with 100% accuracy against a data exchange standard

(Lipman et al., 2010). The perceived conflict phenomenon between the certification body and the end-users is well known in the realm of measurement theory. According to Fenton and Pfleeger (1997, p. 14), “No matter how measurements are used, it is important to manage the expectations of those who will make measurement-based decisions. Users of the data should always be aware of the limited accuracy of prediction and of the margin of error in the measurements”. Therefore, a fundamental problem with the current conformance tests and certification process is the failure to accurately convey the capability of a software tool to interoperate with the data exchange standard through to the end-users.

More insights on the problem can be gained by analysing the conformance test methodologies with respect to the measurement theory. According to the representational theory of measurement, measurement is defined as “a mapping from the empirical world to the formal, relational world” (Fenton & Pfleeger, 1997, p. 28). There are two types of measurements, direct measurements and indirect measurements. Direct measurements are made when an attribute of an entity can be directly mapped into a measure (e.g. measuring the length of an object). Indirect measurements are made when a measure can only be derived from more than one attribute of the entity (e.g. the density can only be measured indirectly by dividing mass by volume of the object). An indirect measure needs a ‘model’ to represent the relation between the attributes measured. In the above example [density=mass/volume] is the model. A model is an abstraction of reality that can strip away the details and allows one to view an entity from a particular perspective (Fenton & Pfleeger, 1997). As per the representational theory of measurement, an indirect measurement process should have three components: 1) a process for the actual measurement of the attributes; 2) a model to define the mapping of the measured attributes; and 3) a measure derived from the model represented in a particular scale. Representing the mapping in a scale enables one to compare and manipulate the various measurements made.

In the case of conformance tests in the BIM domain, the needed measure is the ‘interoperability’ between a software tool and the data exchange standard. A BIM interoperability measure can be defined as the degree of accuracy in preserving the syntactic and semantic correctness of the BIM model when data is exchanged between a BIM software tool and a data exchange standard. Interoperability cannot be measured directly from one single attribute. Hence, it is an indirect measurement, needing all three components recommended by the measurement theory. Current conformance tests only have the first component, i.e. the actual measurement of the attributes. They lack a model that defines interoperability and lack a scale which allows one to convey the level of the measured interoperability. Therefore, the current conformance testing methodologies in the BIM domain do not fully comply with the measurement theory, and they do not qualify as interoperability measurement models. This is one reason for the failure of current approaches to accurately convey the interoperability of BIM software tools.

It is worthwhile to understand how interoperability is measured and expressed in other domains to investigate how closely they conform to the measurement theory and whether any of their approaches are useful for BIM. This study sets out to give insights into transforming the current conformance tests from a meagre ‘testing for interoperability’ to the ‘measurement of interoperability’ in BIM. Initially, a systematic literature review (SLR) on interoperability measurement was conducted. This SLR identifies and analyses existing interoperability measurement methodologies from all domains. The review has identified 28 interoperability measurement models that are from the military, government agencies, and enterprise sectors, though none was found in the AEC (Architecture, Engineering, and Construction) domain. Although these models are from different domains, the definition of interoperability given by each of the models is very similar to that used in the BIM domain. Hence, these models can provide significant insights on adapting or developing a new, interoperability measurement methodology for the BIM domain. Section 2 of the paper explains the SLR methodology and lists out the results. Section 3 analyses and categorises the 28 interoperability measurement models. Section 4 discusses the possibility of adapting one, or more, of these approaches to enhance or complement the current conformance testing methods in the AEC domain with the ultimate objective of developing a true interoperability measurement model for BIM.

2. Systematic literature review methodology

The SLR methodology was formulated as per the guidelines of Kitchenham (2004). The research questions for the SLR were derived to address three viewpoints: population (systems of entities where interoperability issues exist); intervention (interoperability measurement models); and outcome (how these models can quantify interoperability) (Kitchenham, 2004). Three research questions were derived from the above-mentioned viewpoints, where RQ1 combines the population and intervention viewpoints and RQ2 and RQ3 are related to the outcome. The questions are as follows:

RQ1 What measurement models are currently available for interoperability measurement in general?

RQ2 How do existing interoperability measurement models quantify interoperability?

RQ3 Are there any frameworks or methodologies aligned towards interoperability measurement in the BIM or AEC/FM sector. If yes, how are they aligned?

A scoping study and search were conducted on the topic of 'interoperability measurement'. A scoping study allows one to rapidly map the key concepts and the main sources of the proposed research areas (Arksey & O'Malley, 2005). Four review papers were identified, and a snowball search was conducted on those review papers. Fifteen papers which proposed an interoperability model were gathered as the result of the snowball search. Then the databases where those fifteen papers were published were selected as the SLR search databases. The selected databases are: 1) Defence Technical Information Center; 2) IEEE Xplore; 3) Wiley online library; 4) Gridwiseac.org; 5) Springer link; and 6) Science Direct. The keywords for the main search were derived from the titles and abstracts of those fifteen papers. The keywords were: Interoperability; Framework; Measurement; Spectrum; Quantify; Model; Assess; Metric; Federate; Evaluate; Maturity; and Standard. The search terms were constructed and modified with appropriate wild card characters as per the requirements for each database. For example, the search string for IEEE Xplore was: (("Document Title":interop*) AND ("Abstract":interop*) AND ("Abstract":Framework OR "Abstract":Measure* OR "Abstract":Spectrum OR "Abstract":Quanti* OR "Abstract":Model OR "Abstract":Assess OR "Abstract":Metri* OR "Abstract":Federate OR "Abstract":Evaluate OR "Abstract":Maturity OR "Abstract":Standard))

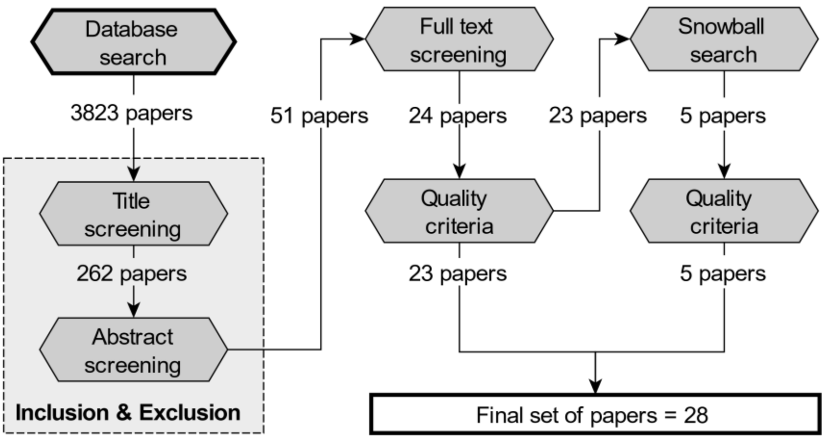


Figure 1: SLR search process

The search process is shown in Figure 1. The search of the six databases returned 3,823 papers, published between 1980 and 2017. A title screening was performed on the search results and 262 papers were shortlisted. After reading the abstracts of the shortlisted papers, 51 papers were selected for the full-text screening. Finally, 24 papers were selected after the full-text screening. Then, quality criteria were applied on the final papers and one paper was rejected, leaving 23 papers as the final result of the database search. Then, a snowball search was performed on the final 23 papers to make sure no papers were missed. The snowball search was able to identify another 5 papers and they all passed the quality criteria test. Additionally, 2 other papers were identified, but their sources are not currently accessible, and so they have been excluded from the result. Therefore, 28 papers were selected as the final set after the entire SLR process. The final 28 interoperability measurement models are listed in Table 1 in chronological order of their publication dates. Details about each of the models are described in a technical report (Jabin, Dimyadi, & Amor, 2019).

Table 1: Interoperability measurement models

#	**Model name**	**Model**
1	Spectrum of Interoperability Model (Lavean, 1980)	SoIM
2	Quantification of Interoperability Methodology (Mensh, 1989)	QoIM
3	Military Communications and Information Systems Interoperability (Amanowicz & Gajewski, 1996)	MCSI
4	Interoperability Assessment Methodology (Leite, 1998)	IAM
5	Levels of Information System Interoperability (C4ISR, 1998)	LISI
6	Organizational Interoperability Maturity Model for C2 (Clark & Jones, 1999)	OIM
7	Stoplight (Hamilton Jr, Rosen, & Summers, 2002)	SL
8	Layers of coalition interoperability (Tolk, 2003)	LCI
9	Levels of Conceptual Interoperability Model (Tolk & Muguira, 2003)	LCIM
10	System-of-Systems Interoperability (Morris, Levine, Meyers, Place, & Plakosh, 2004)	SoSI
11	Non-Technical Interoperability Framework (Stewart, Cremin, Mills, & Phipps, 2004)	NTI
12	Organizational Interoperability Agility Model (Kingston, Fewell, & Richer, 2005)	OIAM
13	The Layered Interoperability Score (Ford & Colombi, 2007)	i-Score
14	GridWise Interoperability Context-Setting Framework (GridWise Architecture Council, 2007)	GwICSF
15	Government interoperability maturity matrix (Sarantis, Charalabidis, & Psarras, 2008)	GIMM
16	Enterprise Interoperability Framework (Chen, Vallespir, & Daclin, 2008)	EIF
17	Maturity model for enterprise interoperability (Guédria, Chen, & Naudet, 2009)	MMEI
18	Business Interoperability Quotient Measurement (Zutshi, Grilo, & Jardim-Goncalves, 2012)	BIQMM
19	Customizable interoperability assessment methodology (Cornu, Chapurlat, Quiot, & Irigoin, 2012a)	CIAM
20	Interoperability assessment in the deployment of technical processes (Cornu, Chapurlat, Quiot, & Irigoin, 2012b)	IADTP
21	Semantic interoperability assessment (Yahia, Aubry, & Panetto, 2012)	SIA
22	A reliability-based measurement of interoperability for systems of systems (Jones, Domerçant, & Mavris, 2013)	RBMoL
23	Ultra-large-scale systems interoperability framework (Rezaei, Chiew, & Lee, 2013)	ULSSIF
24	Testing VM interoperability at an OS and application level (Lenk et al., 2014)	TIOSA
25	A novel approach IMA of interoperability measurement (Koulou, El Hami, Hmina, Elmir, & Bounabat, 2016)	IMA
26	Disaster Interoperability Assessment Model (Da Silva Avanzi, Foggiatto, Dos Santos, Deschamps, & Loures, 2016)	DIAM
27	INTERO - an Interoperability Model for Large Systems (Spalazzese, Pelliccione, & Eklund, 2017)	INTERO
28	Semantic interoperability evaluation model for devices in automation systems (Dibowski, 2017)	SIEMoD

Table 2: Type of model versus Scale

Scale / Type	Nominal	Ordinal	Ratio	Absolute
Maturity levels		SIEMoD, GwICSF, LCI, LCIM		
Maturity matrix		LISI, OIM, GIMM, OIAM		
Interoperability Matrix	TIOSA	SoIM, EIF		
Graded Interoperability Matrix			RBMoL, MMEI, ULSSIF	
Stoplight estimates	SL			
Scores	NTI		SIA, CIAM	i-Score, QoIM, IMA, IADTP
Coordinate estimates			MCISI	
Multivariate estimates		INTERO	DIAM	

3. Analysis

An initial analysis on the 28 models investigated which ones had incorporated all three components of the measurement process. Most of the papers focused on the second and third components of the measurement process. LISI was the only model that gave a clear description of the first component, i.e. how the actual interoperability of entities was measured. Since this study aims to gain an insight into how to represent the measured interoperability between a software tool and a data exchange standard in conformance tests in the BIM domain, the analysis of the 28 models focused on their measurement outcome, i.e. how they represented the interoperability between entities. The measurement theory recognises five major scales, namely nominal, ordinal, interval, ratio, and absolute (Fenton & Pfleeger, 1997). Three measurement models (IAM, SoSI, and BIQMM) analysed were framework models that did not provide a plot of the measurement outcome in terms of any scale. These models suggested that the analysts themselves could select an appropriate scale to represent the outcome. A major difference in representing a measurement outcome on different scales is the ability to undertake different levels of comparison between measured entities. The analysis of the 28 models found that the models represented interoperability on all the scales except for the interval scale. However, it was observed there were major differences in the type of representation of measurement outcomes for the models which fell into the same scale type. Hence, this study developed a ‘type of model versus scale’ categorisation to find out the number of unique ways the available interoperability measurement models have represented interoperability. Table 2 lists out the remaining 25 models which have represented their outcome in one of the four major scales against different types of representation. Thus, it is found that interoperability has been represented in twelve unique ways as per the interoperability models gathered in this SLR. The following subsections discuss each of the observed scales.

3.1. Nominal scale measures

Nominal scales are the most primitive form of measurement that consists only of different classes with no notion of ordering among the classes. Any distinct symbolic or number system is an acceptable measure, and there is no notion of the magnitude of difference associated with the numbers or symbols (Fenton & Pfleeger, 1997). Three models represent interoperability on a nominal scale. The simplest of the models is SL (Hamilton Jr et al., 2002) and comes under the stoplight category. This type of representation is called stoplight because it cautions the user about the current state of interoperability similar to traffic lights. In this model, each interoperability level is given four colours: red, green, yellow, orange, which denotes different states of interoperability between the entities. TIOSA (Lenk et al., 2014) represents interoperability in a matrix format. In this type of representation, the entities being tested are listed in row and column headers, and the interoperability between them is denoted by the intersecting cell. TIOSA denotes interoperability using three states: 1) Successful; 2) Warning; and 3) Failure. The NTI (Stewart et al., 2004) classifies the measurement outcome into six different scores, which are 1, 2, 4, 8, 12, and 16. These are arbitrary numbers known as the multinational forces co-operability index (identifiers for the classification) and do not signify any order or precedence of the represented interoperability classes.

3.2. Ordinal scale measures

An ordinal scale is basically a nominal scale that has information about the ordering of the classes or categories and enables analysis which is not possible with the nominal scale. The numbers represent ranking only. Hence addition, subtraction and other arithmetic operations have no meaning (Fenton & Pfleeger, 1997). There are eleven models under the ordinal scale, making it the most selected scale for measurement. The ordinal scale may be considered as the 'sweet spot' among the scales, because it combines the ease of representation of the nominal scale, as well as providing useful information about the relative ranking between different classes. SIEMoD, GwICSF, LCI, and LCIM represent interoperability as maturity levels. This type of representation classifies the measured interoperability between entities into various ordered levels. A standard format observed in the models is: the higher the level, the more interoperable. LISI, OIM, GIMM, and OIAM represents measured interoperability in a maturity matrix. A maturity matrix is an extension of a maturity level and can express more information than an individual maturity level. The matrix will have maturity levels represented as row headers and other measured attributes as the column headers, and the elements measured will be listed in the appropriate cells. SoIM and EIF represent interoperability as an interoperability matrix. It is the same kind of representation as in the interoperability matrix type on a nominal scale, except that the values shown in the cells will also convey the level of interoperability. The INTERO model represents interoperability using a radial chart where each arm of the chart represents the interoperability level of each measured attribute.

3.3. Ratio scale measures

A ratio scale is the most accurate scale, which enables more analysis than either the nominal or ordinal scales on the measurement outcome. For example, one can infer from a ratio scale that one software tool is twice as interoperable as another. There is a zero element, representing the total lack of the attribute. The measure starts at zero and increases in equal intervals known as units. It preserves order, the size of intervals between entities, and the ratio between entities (Fenton & Pfleeger, 1997). There are seven models under this scale. The model for representing interoperability on a ratio scale is relatively more complex than the other two scales because a ratio scale model must derive precise numerical values that capture and preserve more details about the measured attributes than other two scales where the model only classifies the attributes into broad classes. RBMoL, MMEI, and ULSSIF express interoperability as a graded interoperability matrix. This type of model assigns a number between 0 and 1 (ratio) in each cell of the matrix. SIA and CIAM represent the interoperability in percentage scores. DIAM represents interoperability for multiple parameters as a number between 0 and 1 on a radial chart. MCISI uses theories from geometry to plot the interoperability as points in multidimensional space, and the distance between the points represents the magnitude of interoperability between the entities. A zero distance means full interoperability and interoperability reduces as the distance increases.

3.4. Absolute scale measures

An absolute scale is a simple scale where the measurements are counts of elements in the entity set. The models in this category count some aspects of the measured entities. An absolute scale always takes the form "number of occurrences of x in the entity" (Fenton & Pfleeger, 1997). There are four measurement models under this scale which are i-Score, QoIM, IMA, and IADTP. All the models represent interoperability as scores. However, it was observed that even though the final output of these models are in an absolute scale, the measurement model does additional calculations on the counts to convey more information about the measurement. For example, QoIM further calculates a value for each component measured called Rx, which is the ratio of the total number of positive events out of the total number of events. This calculation brings in aspects of a ratio scale, but the model does not combine multiple Rx values into one final ratio, which leaves the output as individual absolute scores for each interoperability component measured.

4. Discussion

BIM is no longer an experimental technology and is being used in residential through to mega projects across the world. Being a certification body for BIM is a serious responsibility, especially when the technology being certified is used in critical applications where a failure of the certified system can result in the loss of life. It is a risky proposition when "no certification scheme can guarantee completely error-free operation" (Steinmann, 2018), and the certification process fails to convey this message to the end-user who may expect 100% error-free operation from a certified system (Lipman et al., 2010). Data accuracy while exchanging building designs is extremely crucial. For example, the information about a load-bearing structure getting altered while sending a 'good for construction' design to the contractor may cause a catastrophic failure of the structure. The test reports from individual researchers who have tested the accuracy of the data exchange of certain certified software tools are disturbing. Researchers have found a change in position and orientation for structures like columns and found missing load-bearing components after an import-export cycle (round-tripping) of the test BIM models (Lee, Won, Ham, & Shin, 2011; Ma, Ha, Chung, & Amor, 2006). When end-users are unaware that the certified software tools still have interoperability problems, they will not exercise necessary precautionary measures to counter the problems, and this has the potential for disastrous consequences. Therefore, it is necessary to advance research on upgrading the current conformance testing methods in the BIM domain into a true interoperability measurement methodology that can convey the results and the limitations of the measurement outcome without any ambiguity for the end-users.

The current conformance tests for BIM publish the test outcomes as a list of conforming and non-conforming attributes (buildingSMART, 2019), or as the number of attributes that cause some error (NIBS, 2014). As per the measurement theory, these conformance test results can only be classified as a 'quantified indication' (the first component of the measurement process). According to the model-based account of measurement, a quantified indication is "not yet a claim about any aspect of the object or event intended to be measured, but only a mathematical description of the final state of the measuring apparatus [the conformance tests, in this context]" (Tal, 2017). Hence, the current conformance tests need to be further enhanced to become interoperability measurement methodologies. To achieve this, conformance tests need a measurement outcome and a model. A measurement outcome is defined as "a knowledge claim associating one or more parameter values with the object or event being measured" (Tal, 2017). Tal (2017) also specifies that to obtain the status of a measurement outcome, a knowledge claim must be abstracted away from the concrete method of the actual measurement and should typically be expressed in some unit on a particular scale. The abstraction can be done by developing a model of the measure to be represented, i.e. the second component of the measurement process (Fenton & Pfleeger, 1997). Once the measurement outcome is derived using the model from the quantified indications, it should be represented on a scale. One set of quantified indications may be represented in many scales depending upon the model created. In the measurement theory, this is called the 'uniqueness problem'. The problem arises from the question: what should be done when there are several different possible scales (representations) for the same set of quantified indications? (Fenton & Pfleeger, 1997). To answer this question in the context of interoperability measurement in BIM, one should study the major scales used in the measurement theory and analyse the various possibilities of representing interoperability in those scales. Hence, the 28 interoperability models gathered through SLR were analysed from the angle of how they represented interoperability measurement outcomes. With the insights gained, two probable methods for representing IFC conformance tests within the existing processes are suggested by this study.

Since IFC already have a conformance test conducted by buildingSMART that provides the quantified indications (buildingSMART, 2019), this study uses it as an example to show how the quantified indications can be transformed into a measurement outcome. In the case of the current conformance test for IFC the quantified indications are a list of attributes tested for interoperability and each attribute after testing is assigned one of the following three values: 1) supported; 2) restricted; or 3) not supported (buildingSMART, 2019). This test may be upgraded into a proper measurement by converting the quantified indication into a measurement outcome. The simplest possible method to upgrade the current conformance test into a measurement method is to adopt the nominal scale combined with aspects from the absolute scale. This can be easily done because the quantified indications are already classified into three categories (supported, restricted, and not supported), and the total number of occurrences of these three attributes are already counted and displayed in the summary page. For example, the grand total of these assigned values may be calculated and displayed as a single score under three distinct categories. The rules defining how to calculate the total sum will become the model of this measurement method. Each sum behaves like values of an absolute scale, which are then classified into three distinct classes represented on the nominal scale. This final classification could be shown along with the certification logo. Displaying the measurement outcome along with the certification logo will convey to the end-user that the software tool is certified with some limitations, such as a number of attributes are not supported or are restricted (buildingSMART, 2019).

The drawback of the measure described above is that it does not convey the criticality of the unsupported and restricted attributes. For example, an unsupported attribute like ‘Placement Relative’ (name of an attribute tested) might be more critical than an unsupported ‘Geometry Axis’ in IfcFastener class (buildingSMART, 2019). Also, the final measurement outcome does not convey any information regarding the overall level of interoperability of the software tool. This problem can be solved by developing a different model that assigns a weighting for each attribute according to its criticality. For example, the equation [1 - (weights of unsupported attributes / total weights)] will give the level of interoperability of the tested software tool with a given IFC schema. A similar calculation can also be carried out with the restricted attributes (using different weights), and then both can be combined to give the final interoperability value. The resulting value will be on a ratio scale that gives the end-user more clarity on the overall interoperability of the software tool. This shows that it is possible to represent the measurement outcome in different ways by developing different models for the same quantified indicators.

5. Conclusion

The current conformance tests in the BIM domain do not conform to the measurement theory and consequently are not capable of accurately conveying the measurement outcome and limitations of the measure to the end-users. Other domains have used different representations for the metrics of interoperability. These can be adapted by the current conformance test processes to make them a true interoperability measurement methodology. To ensure that end-users are provided with the precise meaning of the conformance test, there needs to be further work on how current conformance tests can be revamped into true interoperability measurement methodologies. The suggested method of adapting measurement methods from other domains can serve as a starting point for further research.

A limitation of this work is that the suggested measures in this study are only an example of what could be done to upgrade the current BIM conformance test methodologies. As measurement theory is an established field in science, there is great potential to further explore the development of various models to define interoperability in BIM and represent it in an appropriate scale using techniques and methods from the measurement theory. Further research is being conducted by the authors to develop the best possible model to measure and represent interoperability of a BIM software tool against a selected data exchange standard.

6. References

Amanowicz, M., & Gajewski, P. (1996). *Military communications and information systems interoperability.* Proceedings of MILCOM '96 IEEE Military Communications Conference, McLean, VA, USA. *1*, 280-283

Amor, R., & Dimyadi, J. (2010). *An Open Repository of IFC Data Models and Analyses to Support Interoperability Deployment.* Proceedings of 27th CIB W78 International Conference, Cairo, Egypt, 16-18

Arksey, H., & O'Malley, L. (2005). Scoping studies: towards a methodological framework. *International journal of social research methodology, 8*(1), 19-32.

buildingSMART. (2010). Specification of IFC Certification 2.0 Process. Retrieved September 3, 2019, from https://standards.buildingsmart.org/documents/bSI_IFC_Certification_2-0_Specification_Final.pdf

buildingSMART. (2019). Certified Software. Retrieved April 7, 2019, from https://www.buildingsmart.org/compliance/certified-software/

C4ISR. (1998). *Levels of information systems interoperability (LISI)*. Retrieved from http://web.cse.msstate.edu/~hamilton/DODAF/LISI.pdf

Chen, D., Vallespir, B., & Daclin, N. (2008). *An Approach for Enterprise Interoperability Measurement.* Proceedings of MoDISE-EUS, Montpellier, France, 1-12

Clark, T., & Jones, R. (1999). *Organisational interoperability maturity model for C2.* Proceedings of the 1999 Command and Control Research and Technology Symposium, Newport, RI, USA, 1-13

Cornu, C., Chapurlat, V., Quiot, J.-M., & Irigoin, F. (2012a). Customizable interoperability assessment methodology to support technical processes deployment in large companies. *Annual Reviews in Control, 36*(2), 300-308.

Cornu, C., Chapurlat, V., Quiot, J.-M., & Irigoin, F. (2012b). *Interoperability Assessment in the Deployment of Technical Processes in Industry*. Proceedings of INCOM 2012, The 14th edition of IFAC's triennal symposium INCOM, Bucharest, Romania, F20-F25

Da Silva Avanzi, D., Foggiatto, A., Dos Santos, V. A., Deschamps, F., & Loures, E. d. F. R. (2016). A framework for interoperability assessment in crisis management. *Journal of Industrial Information Integration, 5*, 26-38.

Dibowski, H. (2017). *Semantic interoperability evaluation model for devices in automation systems.* Proceedings of Emerging Technologies and Factory Automation (ETFA), 22nd IEEE International Conference, Limassol, Cyprus, 1-6

Fenton, N., & Pfleeger, S. (1997). *Software Metrics: A Rigorous Practical Approach* (2nd ed.). Boston, MA: PWS Publishing Company.

Ford, T., & Colombi, J. (2007). *The interoperability score.* Proceedings of the 5th conference on systems engineering research, Hoboken, NJ, USA, 1-10

GridWise Architecture Council. (2007). GridWise Interoperability Context- Setting Framework. *The GridWise Architecture Council*, 1-52.

Guédria, W., Chen, D., & Naudet, Y. (2009). *A maturity model for enterprise interoperability.* Proceedings of OTM Confederated International Conferences On the Move to Meaningful Internet Systems, Vilamoura, Portugal, 216-225

Hamilton Jr, J. A., Rosen, J. D., & Summers, P. A. (2002). An interoperability road map for C4ISR legacy systems. *Acquisition Review Quarterly-Winter 2002*, 17-31.

Jabin, J., Dimyadi, J., & Amor, R. (2019). *Systematic literature review on interoperability measurement models* [Technical report]. doi: 10.13140/RG.2.2.33957.35047

Jones, W., Elizabeth, Domerçant, J. C., & Mavris, D. N. (2013). *A reliability-based measurement of interoperability for systems of systems.* Proceedings of Systems Conference (SysCon), 2013 IEEE International, Orlando, Florida, USA, 408-413

Kingston, G., Fewell, S., & Richer, W. (2005). *An organisational interoperability agility model.* Proceedings of 10th ICCRTS, Virginia Beach, VA, USA, 1-18

Kitchenham, B. (2004). *Procedures for performing systematic reviews* [Technical report]. Retrieved from Keele University website http://www.inf.ufsc.br/~aldo.vw/kitchenham.pdf

Kiviniemi, A. (2008). *IFC Certification process and data exchange problems.* Proceedings of the 7th European Conference on Product and Process Modelling (ECPPM 2008), Sophia antipolis, France, 517-522

Koulou, A., El Hami, N., Hmina, N., Elmir, A., & Bounabat, B. (2016). *A novel approach IMA of interoperability measurement.* Proceedings of Information Science and Technology (CiSt), 2016 4th IEEE International Colloquium on Information Science and Technology, Tangier, Morocco, 665-669

Lavean, G. (1980). Interoperability in defense communications. *IEEE transactions on communications, 28*(9), 1445-1455.

Lee, G., Won, J., Ham, S., & Shin, Y. (2011). Metrics for Quantifying the Similarities and Differences between IFC Files. *Journal of Computing in Civil Engineering, 25*(2), 172-181.

Leite, M. J. (1998). *Interoperability assessment.* Proceedings of the 66th Military Operations Research Society Symposium, Monterey, CA, USA, 1-13

Lenk, A., Katsaros, G., Menzel, M., Revelant, J. R., Skipp, R., Leon, E. C., & Gopan, V. (2014). *TIOSA: Testing VM Interoperability at an OS and Application Level-A Hypervisor Testing Method and Interoperability Survey.* Proceedings of Cloud Engineering (IC2E), 2014 IEEE International Conference, Boston, Massachusetts, USA, 245-252

Lipman, R., Palmer, M., & Palacios, S. (2010). Assessment of conformance and interoperability testing methods used for construction industry product models. *Automation in Construction, 20*, 418-428.

Ma, H., Ha, K. M. E., Chung, C. K. J., & Amor, R. (2006). *Testing semantic interoperability.* Proceedings of Joint International Conference on Computing and Decision Making in Civil and Building Engineering (ICCCBE), Montreal, Canada, 1216-1225

Mensh, D. R. (1989). The quantification of interoperability. *Naval Engineers Journal, 101*(3), 251-259.

Morris, E., Levine, L., Meyers, C., Place, P., & Plakosh, D. (2004). System of Systems Interoperability (SOSI) Final Report. *Integration of Software-Intensive Systems Initiative*, 1-53.

NIBS. (2014). January 2014 bSa Challenge: Graphisoft. Retrieved April 16, 2019, from https://www.nibs.org/page/bsa_chall14_gs

Rezaei, R., Chiew, T. K., & Lee, S. P. (2013). An interoperability model for ultra large scale systems. *Advances in Engineering Software, 67*, 22-46.

Sarantis, D., Charalabidis, Y., & Psarras, J. (2008). Towards standardising interoperability levels for information systems of public administrations. *The Electronic Journal for E-commerce Tools*

& Applications (eJETA) Special Issue on Interoperability for Enterprises and Administrations Worldwide, *2*, 1-15.

Spalazzese, R., Pelliccione, P., & Eklund, U. (2017). INTERO: an Interoperability Model for Large Systems. *IEEE Software*, 1-11.

Steinmann, R. (2018). IFC Certification of BIM Software. In *Building Information Modeling Technology Foundations and Industry Practice* (pp. 139-153). Cham, Switzerland: Springer Nature.

Stewart, K., Cremin, D., Mills, M., & Phipps, D. (2004). *Non-technical interoperability: the challenge of command leadership in multinational operations.* Proceedings of the 10th International Command and Control Research and Technology Symposium: The Future of C2, McLean, VA, USA, 1-9

Tal, E. (2017). A Model-Based Epistemology of Measurement. In *Reasoning in Measurement* (pp. 233-251). New York, NY: Routledge.

Tolk, A. (2003). *Beyond technical interoperability-introducing a reference model for measures of merit for coalition interoperability.* Proceedings of 8th International Command and Control Research and Technology Symposium, Washington DC, USA, 1-46

Tolk, A., & Muguira, J. A. (2003). *The levels of conceptual interoperability model.* Proceedings of the 2003 fall simulation interoperability workshop, Orlando, Florida, USA. *7*, 1-11

Yahia, E., Aubry, A., & Panetto, H. (2012). Formal measures for semantic interoperability assessment in cooperative enterprise information systems. *Computers in Industry, 63*(5), 443-457.

Zutshi, A., Grilo, A., & Jardim-Goncalves, R. (2012). The business interoperability quotient measurement model. *Computers in Industry*, *63*(5), 389-404.

BIM in the Water Industry: Addressing Challenges to improve the project delivery process

Suresh Renukappa[1,*], Subashini Suresh[1] and Andrew Kamunda[1]
[1]University of Wolverhampton
* email: Suresh.Renukappa@wlv.ac.uk

Abstract

The UK Government BIM implementation 2016 target for all public projects formed the major driver for the construction industry to upskill and learn new ways of working. The water industry is a private sector that has no mandate to implement BIM and would also benefit from its use. Research has identified that fragmentation and inefficiency still existed in the water industry project delivery processes. These issues can be addressed by harnessing the collaboration that BIM brings by using emerging information technology. The UK water industry has had little research in the use of BIM in the project delivery processes over the years. Therefore, the aim of the research is to explore and examine BIM use in the water construction industry, as well as understand the challenges faced and how they are being addressed to improve project delivery processes. The qualitative case study approach was adopted for the collection and analysis of data which was carried out by undertaking observations, document reviews and semi structured interviews. A water company and a design and build contractor on a framework formed the research sample. The design and build contractor was also part of other water industry frameworks. The research findings identified that there are similarities between the water industry and the other infrastructure sectors in the use of BIM realizing benefits of collaborative working. These benefits included improved information quality, cost reductions, shorter programme durations and greater collaboration. However, BIM was yet to be fully understood and used which led to challenges of overcoming and changing organizational cultures, developing levels of BIM expertise, data and information control, interoperability and data entry. The research also identified that the water company was lagging in BIM use despite noticeable benefits shown by its supply chain. The paper concludes by identifying that the water industry supply chain has taken positive steps and started to benefit from BIM use. However, more needs to be done as BIM is still in its infancy facing challenges associated with changing organizational cultures. The research recommends that the water industry and its supply chain should continue to invest more resources in implementing BIM to achieve the benefits realized by other sectors with NBS and CITB becoming more visible. This should include staff training, creating standardized approaches, processes to harness the collaborative nature of BIM.

Keywords: BIM, water industry, challenges

1. Introduction

The UK water industry has been undergoing significant changes which have impacted on water companies and its supply chain. Since the water industry's privatization 25 years ago, over £100 billion have been spent (NCE, 2014a). The National Audit Office (NAO, 2015) expects a capital expenditure of £44 billion in Asset Management Period (AMP) 6 (2015-2020) whereas Hackett (2018) predicts an expenditure of £50 billion in the next AMP7 (2020 to 2025) which is a 13% uplift from AMP6. However, there have been calls for infrastructure investments to be based on sustainable and efficient solutions to meet an increase in population, climate change and technological changes. Most of the existing water infrastructure is the creation of engineering innovations from Victorian times. Although this is an incredible legacy, it has not been nurtured as it should be particularly over the last forty years. Until recently, capital investment programmes have been undertaken to varying degrees by the water companies to upgrade its infrastructure (CST, 2009).

Back in 2006, Rezgui and Zarli (2006) highlighted that the construction industry was moving from using traditional physical elements to information technology software with intelligence. This was supported by Hardin and McCool (2015) who pointed out that the construction industry was in the midst of a technology renaissance; however, the new technology did not fit into the previous project delivery processes. The NCE (2014) further ruled the processes as inefficient needing more collaboration and integration. These processes were also deemed broken in 2017 leading to delivering expensive assets, poor performance and failed to make best use of emerging technology (ICE, 2017). The use of collaborative Building Information Modelling (BIM) presents opportunities to remove these inefficiencies (Owen, et al, 2010). Using BIM involves sharing of information and presents diversity of risk areas hence there is a need to identify challenges and barriers which becomes a prerequisite to its application (Khosrowshahi and Arayici 2012).

The UK Government mandate for use of BIM for all public projects starting in 2016 formed the major driver for the construction industry to upskill and learn new ways of working. Big organizations tend to undertake most capital work due to stronger financial positions and likely face more difficulty in the use of BIM (Miller, 2012). However, financial implications and skills shortages on BIM implementation were cited by Sinclair (2012) as barriers. Azhar et al, (2008) identified model ownership as the first barrier for BIM use. These challenges might become hindrances to project progression if not addressed.

The UK Government has stated a key aspiration for the construction industry to be efficient and technologically advanced through the Construction Strategy 2025 (HM Government, 2013). There is emphasis on the use of BIM being able to form a basis for meeting efficiency and technological 2025 targets. These targets include achieving 33% cost efficiency, delivering 50% faster and achieve 50% reduction in greenhouse gases emissions. However, there is a realization that there is a great challenge to fully embrace and implement BIM (HM Government, 2013). This provides a significant driver for this research project for water industry projects.

Schefer in the NCE (2014) stated that there is a need to think differently. Water companies and its supply chains must be more integrated and collaborative. Inherently, most water companies are set up around planning, delivery and operations as different departments with a breakage somewhere between the two components. BIM would solve the above stated issues if BIM is used correctly (Kemp, 2014). Furthermore, significant efficiencies, cost savings and improved delivery of client's value in construction can be achieved by correctly utilizing BIM (ICE, 2015). It was expected that BIM will advance its importance in the UK water sector AMP6 period (NCE, 2015a).

Rezgui et al, (2009) stated that despite the advantages that follow BIM utilization, there are several issues that have derailed its adoption. The concerns include trust, authentication, security, validation, quality, ownership and other related issues. By addressing these concerns and challenges construction projects would yield the benefits associated with effective BIM use. In addition, UK water projects will meet the objectives set by Ofwat and address the shortfalls identified by Latham (1994) and Egan (1998).

2. The UK Water Industry: Then and Now

2.1 The Water Industry History

The water industry was disjointed up to and through the Second World War, with development required due to an increase in water demand, industrial revolution, economic growth and population increase. A drought in 1959 and flooding in 1960 led to the recognition of the importance of collaborative planning and to the creation of the Water Resources Act in 1963. However, planning challenges continued in the 1960s and 1970s which resulted in the restructuring of the water industry; ten water regional authorities were established to manage water resources & supply and water & sewerage services on a full-time basis in adherence to the Water Act, 1973. Economic challenges in the 1970s and 1980s led to changes in the legislation with the Water Act, 1983 reducing the government's decision making whilst local authorities could seek private investment (Ofwat and Defra, 2006).

However, these approaches and changes failed to yield the intended benefits and led to the privation of the water companies in 1989 to access private funding. The privatization led to the creation of three regulatory bodies which represented the public interests, The National Rivers Authority (superseded by the Environment Agency), Office of Water Services and Drinking Water Inspectorate (Ofwat and Defra, 2006).

2.2 The Water Industry Today

The industrial revolutions, urbanization, increasing economic demands and increasing environmental requirements shaped the status (Ofwat and Defra, 2006). The UK water industry's key purpose is to provide safe drinking water and effective wastewater management (CIWEM, 2010). It consists of relatively small Water Only Companies (WOCs), and Water and Sewerage Companies (WaSCs), which are larger and offer water supply and sewerage services (Hainworth and Salvi, 2017). These can be regional or local companies, (a) water supply and (b) water supply & sewerage licensees and infrastructure providers delivering large infrastructure projects. Most customers are served by monopoly water companies for their water and sewerage services (Ofwat, 2019). See Table 1 below.

Table 1: UK WOCs and WaSCs (Hainworth and Salvi, 2017)

Water and Sewerage Companies	***Customer (millions)***	***Water Only Companies***	***Customer (millions)***
Anglian	*6.7*	*Affinity*	*3.5*
Dwr Cymru (Welsh Water)	*4.1*	*Bristol*	*1.1*
Northern Ireland	*1.8*	*Dee Valley*	*0.3*
Northumbrian (inc Essex & suffolk)	*3.6*	*Portsmouth*	*0.7*
Scottish	*6.7*	*Bournemouth*	*0.5*
Severn Trent	*10.4*	*South East*	*2.1*
South West	*1.6*	*Sutton & East Surrey*	*0.7*
Southern	*4.6*	*South Staffordshire (including Cambridge)*	*1.6*
Thames	*14.9*		
United Utilities	*8.5*		
Wessex	*3.1*		
Yorkshire	*6.0*		

he UK water industry operates on five-year cycles, called Asset Management Planning periods (AMP) where projects are planned, and budgets set. Under the regulation of Ofwat, (The Water Services Regulation Authority) water companies submit price reviews (PR) to Ofwat which detail their proposals on how they intend to deliver customer needs and wants, the latest being PR19, i.e. Price Review 2019.

Ofwat reviews them and provides water companies with feedback on either approval, rejection, requirement for more information or revision of proposals (Ofwat, 2019).

Bailey (2003) stated that the water industry's significant capital works is carried out and provided by the construction industry engineering and construction organizations. These organizations form the supply chain which has technical expertise that allows them to undertake capital works as delivery partners to the private water companies. To date, creation of frameworks, with fewer partners in a settled supply chain have been undertaken in response to the publication of the Egan and Latham reports which highlighted the need for greater collaboration between clients and the supply chain (Cabinet Office, 2011). Anglian Water named its framework partners for the current and future AMP in 2014 with contracts that span 15 years (Anglian Water, 2014). Back in 2013, Thames Water's Asset Director Lawrence Gosden, stated that "*the decision to deliver the investment programme using an alliance marked a complete transformation in the way the company delivers capital investments*" (Thames Water, 2013). United Utilities, Wessex Water, Severn Trent Water, Southern Water, Yorkshire Water and Welsh Water are other companies that have also created frameworks (Construction Enquirer, 2015).

2.3 The Water Project Delivery Process

Most UK construction projects are delivered following the model developed by the Royal Institute of British Architects (RIBA) called the Plan of Work. The Plan of Work is a process model for delivering building and construction projects which provides a shared framework for organization and management. It is widely used as a process map and a management tool providing work stage reference points, in a multitude of contractual, appointment documents and best practice guidance (RIBA, 2012).

Stage 0 is developing of strategies which define project descriptions (RIBA, 2012). Water companies' Project Reviews submission to Ofwat form Stage 0 for some projects, which are prepared carried out their internal teams (Ofwat, 2015). The project is strategically appraised and defined before preparing a detailed project brief. The strategic definition stage which is also called the inception stage, is where the decision to invest in a construction or development project is made (CIOB, 2010).

During Stages 0 and 1, the Project Brief is developed which is a description of the project scope. Stage 2 is for Concept Design development and includes preparing outline designs, specifications, proposals, strategies and cost data whereas Stages 3 and 4 are for design development which lead into construction i.e. Stage 5. The next stages 6, and 7 are handover, and operation and maintenance respectively (RIBA, 2012 and Anglian Water, 2014).

2.4 BIM in the Water Industry Project Delivery Process

The Construction Project Information Committee (CPIC) (2015) defines BIM as "*digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition*". BIM itself is not a technology but a data rich model-centric business process with the power to transform project delivery. This transformation adds value across the full lifecycle of infrastructure assets – plan, design, build and manage. It is a knowledge process about the way to build things (Autodesk, 2015a) and involves creating and utilizing intelligent 3D models (Autodesk 2015b). For the purposes of this paper, the BIM definition by CPIC (2015) will be adopted.

The UK Government BIM Task Group established the BIM4Water Group after publication of the Construction Strategy (BIM4Water, 2015). This is a cross industry group open for all organizations involved in the delivery and management of water and wastewater projects in order to support adoption of BIM. The BIM4Water (2017) Task Group highlighted that BIM is already changing how capital projects are being delivered and how asset information is created and exchanged; this has been delivered benefits and created value opportunities throughout the asset management cycle. These opportunities are driven by use of digital technologies in capital projects.

BIM4Water (2017) regarded BIM as a business change that will take years to fully embed requiring investment in processes, people and systems to yield long term benefits. There is a need to align BIM with data, information, digital strategies and security though there is exists practices across the water industry. This will lead to BIM evolving to become more aligned with national BIM standards to deliver aspirations set out in the UK Government Construction 2025 Strategy. BIM4Water (2017) has called the water industry players to be part of the Digital Britain to enable accessing new efficient ways of working as in the case studies below.

The Anglian Water Recycling Centre Extension project was carried out using BIM which showed significant improvements in business processes yielding delivery time and cost savings. The Semer Water Treatment Works, an Anglian Water project used 3D modelling aligned with programme and the associated commissioning plan which led to removal of significant business risk associated with an old unreliable borehole source. Severn Trent Water use of BIM on the Minworth wastewater treatment facility project led to a £5 million and 13.5% cost saving (BIM4Water, 2019). According to NCE (2014), BIM real benefits go to the client as it can reduce whole life costs of the asset during operations. There is the recognition by clients, contractors and consultants that the significant benefits of BIM use stem from sharing of data throughout the project lifecycle, optimising design performance, reducing errors and reduced project durations. BIM offers a unique opportunity (RIBA, 2012) and is regarded as the driver to revolutionize construction projects delivery. This is a shift from the traditional inefficient paper-based processes with fragmented project teams to a more integrated, seamless transfer of data between collaborators who are incentivized to deliver whole life cost savings (Building, 2014).

Implementing BIM has not been without its challenges as it is a new way of working. Khosrowshahi and Arayici (2012) and RIBA (2012) stated that the main challenges to the use of BIM has been firms not being familiar to its use, unwillingness to train staff, or initiate culture changes or new processes or workflows, unwilling to procure respective software and technology. BIM4Water (2015) goes on further to state there is a need raise BIM awareness through training people on how to manage and using asset data. Other challenges and barriers to BIM adoption include (a) higher expectations from the supply chain, (b) inconsistent or multiple protocols, (c) significant culture change to adopt BIM, (d) lack of informed clients and (e) the need to define new roles. It is apparent that challenges stem from the need to change from business as usual organizational cultures which comes with progression into the unknown BIM environment (BIM4Water, 2017). Hence there is a need to explore and examine use of BIM in a project delivery setting, to understand the challenges and thus identify solutions to solve them. This would enable water projects achieve the cost and programme benefits of using BIM. There is also little research in the area addressing BIM challenges at project delivery team level and this study aims to fill some of these gaps.

3. Research Methodology

A research should be conducted to correspond with the availability of needed data (Neuman, 2014). The research aims, and objectives point towards investigative work as BIM has not fully matured in the water industry despite making some progress and there are limited study findings in the subject (BIM4Water, 2017). Hence, there is a requirement to understand perceptions and experience the project delivery processes in relation to BIM. A qualitative research approach was selected for the research as it is a method of discovering and understanding the meaning of individuals or groups ascribed to a social or human issue (Creswell, 2009) which met the research aim and objectives of understanding what is going on, by what people say or what they do with BIM in the water industry projects.

The study required an in-depth analysis of the water companies and the supply chain's BIM implementation to support the literature findings on benefits achieved by addressing challenges. This pointed towards a case study approach which can elaborate on an entire process holistically and allow incorporation of multiple perspectives (Neuman, 2014). A case study's ability to incorporate multiple data sources and provide detailed account of complex research phenomena in real life context made it suitable. It is regarded as a viable way of carrying out qualitative research and involve in-depth exploration and to supports use arguments with conclusions related to a related topic. Hence the data was collected from the review of two water companies and its supply chain, review of intranets to understand project delivery processes and documents, observing organizations' cultures, behaviors and undertaking selected interviews of five project participants based on theoretical sampling methodology. Two interviewees were BIM technicians, two were project designers and one was a project leader. This sample represented the design team involved in project delivery.

4. BIM in Practice

4.1 Organizational Culture Support for BIM

BIM is regarded as a shift from the traditional way of delivering projects and requires organizational culture process acceptance and changes to implement it. According to Aranda-Mena *et al*, (2009), BIM facilitates integration of fragmented practices and acts as a catalyst for changing business processes. Autodesk (2015a) pointed out that the use of cloud-based technology in BIM allows carrying out multiple iterations of very complex analyses in near real time versus minutes, hours, or days.

The study identified that BIM has already changed how projects are carried out by the two water companies and the supply chain. The organizations had set up information technology systems that allow hosting BIM technology and processes. This includes rolling out of ProjectWise, a collaborative file saving and sharing cloud-based platform and training staff in its use. Project delivery management took the lead in prompting project managers to use BIM, or its elements, during project inception or reviews. One of the study organisations had prepared and implemented a BIM Execution Plan as part of the water company framework, making it a reference document for project delivery. This stated the provided information technology that needed to be used to support BIM (Autodesk Revit, Civil 3D, Navisworks, Piping & Instrumentation Diagrams and Revit to Excel links). The organisation put in place measures to support BIM, as they had identified this as an enabler for realising BIM benefits. This addressed the challenge of procuring the respective BIM software (Khosrowshahi and Arayici, 2012).

BIM4Water (2015) points out that there is a need raise BIM awareness on the need for people training and that upcoming designers and contractors should embrace the new collaborative working methods (RIBA, 2012). During an interview, an individual stated that BIM was in its infancy and is being gradually developed within their organisation. Training support was offered by all the organisations within the study cohort, however some interviewed think that more can be done as this is restricted by organisations allocated budgets. However, in one organisation, BIM Technicians were allocated training budget associated with their skill level and regular training was encouraged by management to ensure that experience was passed onto their respective projects.

The study also observed that none of the two water companies themselves had processes and information technology that supported BIM. BIM4Water (2015) highlighted that the construction industry broadly agrees with BIM intended benefits; however, challenges to be overcome are associated with measuring the benefits and costs consistently and identify recipients of the benefits and justifications. For clients, they would want to identify the problems and what they need to do to meet their regulatory requirements, at the cheapest cost. The study observed that this was the approach for the research cohort as the water companies left BIM use to the supply chain as they deemed them best suited to use it. However, the water companies carried out relatively very small projects which did not justify investing in BIM processes from their own perspective.

4.2 BIM and its Elements in Use

Bernstein and Pittman (2004) cited barriers to broader adoption of BIM as extending beyond the often-stated relationships between software applications to interoperability. The use of IFC is identified by as the solution to interoperability issues. IFC allows exchanging relevant data between different software and is regarded as fundamental to open BIM (NBS, 2017). GCA (2015) implemented BIM by using the Autodesk suite tools which are quite common in engineering design. The use of commonly used engineering Autodesk suite software allowed GCA (2015) to realise saving hundreds of design hours, avoiding problems, saving project time, cost and identifying engineering opportunities in design. Azhar *et al* (2008) and BIM4Water (2017) highlight that BIM can be used for purposes which primarily include *three dimensional* visualisations which are created directly from the models and contain underlying information. (Autodesk, 2015a) provide an example of a BIM water project case study which had integrated 3D model generated for the entire project.

BIM models are regarded as data and information rich with the ability to gain quicker approvals from water company client managers and site operatives. Three dimensional models are shared and present real-life representation of the asset to be built. One of the water company's solution engineers undertook an in-house presentation on a BIM delivered project stating that 3D models enabled site operatives to see what they were getting, which enabled them to recommend their preferences on access to plant and equipment for operations and maintenance activities. However, the water company did not have any information technology systems to create these models but utilised those provided by the delivery partner. To address the barrier or challenge of interoperability, 3D models were generated and embedded in Acrobat pdf software which could be accessed from most computers with free software. As data and information rich, BIM models were also used to extract schedules for procurement of respective equipment and plant. These were extracted to Microsoft Excel and Acrobat pdf files which could be accessed by most project participants. Though not used, use of open BIM would have allowed the delivery partners to share this information through IFC. Despite the young age of BIM in the Water Industry, benefits from the 3D generated views and reality has enabled greater collaboration. There is the coming of age of the ability to extract data and information quicker than before BIM use which is having positive impact on project delivery programme, cost, and quality.

4.3 BIM is here, what's next?

BIM4Water and British Water has enabled meetings of the BIM4Water Owner Operator Group formed in 2016. This group is made up of Water and Sewerage Companies in England, Scotland and Northern Ireland (BIM4Water, 2017). The water industry has been holding several workshops, seminars and events on BIM in the industry. The topics developed were being driven by the ever-increasing use of BIM in the water industry and how to reduce costs for asset owners, suppliers and contractors. It is highlighted that the water sector is beginning to reap the rewards of using BIM with an expectation that it will increase in the coming years (WIF, 2015).

Both water companies in this study form part of the BIM4Water Group and continue to support its goal of supporting the water industry to implement BIM and realize the benefits. BIM is considered to be in its infancy regardless of the years that have passed. Use of emerging technology e.g. Autodesk Revit, Civil 3D, Revizto, and virtual reality has gained traction and is leading organizations continue to invest in these areas to remain relevant. This was identified for all the organizations in this research.

5. Conclusion

The UK water industry has been lacking behind in implementing BIM as it is not mandatory. However, BIM has been adopted since other industries have been achieving positive benefits. These include achieving cost efficiencies, shorter project durations, and better-quality outputs. The water industry supply chain has started invested in procuring respective BIM software to allow them to implement it. The organizations have also put in place processes and cultures to ensure that BIM use steadily increases. However, there are challenges that continue to be faced which include lack of adequate training in some organizations due to budget constraints whereas others are doing well. The key benefits for the Water Industry on BIM implementation include visualizations in three dimensions of the assets to be built to obtain client approvals, improving collaboration as well as designing out inefficiencies. The other use is the ability to extract schedules which are then used for procurement to enable installation during construction.

There is a need for organizations to continue to review what BIM can do for them and how it can improve the way they work as its use increases and organizations continue to invest and develop led by BIM4Water. BIM definition has been explained, with BIM4Water preferring the term “Better Information Management” to make it express a better way of working which is leading to benefits being achieved in the water sector. Organizations should utilize BIM as a tool to create a competitive advantage as it is seen as being cost effective, which reduces project durations and improves quality of the end product. The open BIM platform and use of IFC for the sharing of digital information in different format should be taken advantage of and organizations like NBS & CITB should become more visible to the water industry. This research recommends that further studies are carried out to determine the effects of mandating BIM for water projects as the UK government has done for public projects.

References

Anglian Water (2014, August 26). *Anglian Water names partners for £450 million AMP6 frameworks*. Retrieved from http://www.anglianwater.co.uk/news/anglian-water-names-partners-for-450-million-amp6-frameworks.aspx

Aranda-Mena, G., Crawford, J., Chevez, A. and Froese, T. (2009). Building information modelling demystified: does it make business sense to adopt BIM? International Journal of Managing Projects in Business, 2(3), 419-34

Autodesk (2015a) BIM for Infrastructure: The Impact of Today's Technology on BIM. Retrieved from http://static-dc.autodesk.net/content/dam/autodesk/www/campaigns/eni-owa-your-bim/eni-owa-your-bim-4/technology-whitepaper-04.PDF

Autodesk (2015b,) BIM for Infrastructure: Is Civil Engineering Facing an Age of Extinction? Retrieved from http://static-dc.autodesk.net/content/dam/autodesk/www/campaigns/eni-owa-your-bim/eni-own-bim-2/set2_whitepaper_cost_of_not_using_BIM_uk_new.pdf

Azhar, S., Hein, M. and Sketo, B. (2008). Building Information Modeling (BIM): Benefits, Risks and Challenges. McWhorter School of Building Science, Auburn University, USA

Bailey, P. (2003, February) The Business and Financial Structure of the Water Industry in England and Wales. Retrieved from http://www.bath.ac.uk/management/cri/pubpdf/Research_Reports/14_Bailey.pdf

Beinstein P. G. and Pittman, J. H., (2004) Barriers to the Adoption of Building Information Modelling in the Building Industry. California. Autodesk Building Solutions

BIM4Water (2015) BIM Frequently Asked Questions Retrieved from http://www.bimtaskgroup.org/wp-content/uploads/2013/05/BIM4Water-FAQ.pdf

BIM4Water (2017, July) BIM Guidance for the Water Industry. Retrieved from https://www.britishwater.co.uk/media/Download.aspx?MediaId=1217

BIM4Water (2019). BIM4Water Case Studies. Retrieved from https://www.britishwater.co.uk/bim4water-case-studies.aspx

Building (2014, June 6). CPD 14 2014: BIM – collaboration and the common data environment Retrieved from http://www.building.co.uk/professional/cpd/cpd-14-2014-bim-collaboration-and-the-common-data-environment/5068904.article

Cabinet Office (2011, May). Government Construction Strategy. Retrieved from www.gov.uk/government/uploads/system/uploads/attachment_data/file/61152/Government-Construction-Strategy_0.pdf.

Chartered Institute of Building (CIOB), (2010). Code of Practice for Project Management for Construction and Development (4th Ed.) Oxford. Blackwell

Chartered Institute of Water and Environment Management (CIWEM), (2010, September). Regulation for a sustainable water industry. Retrieved from https://www.ciwem.org/assets/pdf/Policy/Reports/RSWI-FINAL.pdf

Construction Enquirer (2015) AMP6. Retrieved from http://www.constructionenquirer.com/tag/amp6/

Council for Science and Technology (CST), (2009). Improving innovation in the water industry: 21st century challenges and opportunities. Retrieved from http://www.ukwir.org/site/web/news/improving-innovation?xpm64409=65123

Creswell, J. W (2009). Research design: qualitative, quantitative, and mixed method approaches. (4th ed.). Los Angeles. SAGE

Egan, J. (1998) Rethinking construction, Construction Task Force. London. HMSO

Galliford Try, Costain and Atkins (GCA) (2015) BIM in Action: How to Succeed with BIM podcast Retrieved from http://www.autodesk.co.uk/campaigns/eni-own-bim-5/thank-you

Hackett, R. (2018, September 3). Water companies plan £50BN on service improvements in AMP7. Retrieved from https://wwtonline.co.uk/news/water-companies-plan-50bn-on-service-improvements-in-amp7

Hainworth, G. and Salvi, G. (2017) GB Water Industry for Dummies (2nd Ed). Chichester. John Wiley & Sons Ltd

Hardin, B., and McCool., D, (2015). BIM and Construction Management: Proven Tools, Methods and Workflows. Indiana, John Wiley

Holt, G. D. (1998). A guide to successful dissertation study for students of built environment. (2nd Ed.) Wolverhampton: University of Wolverhampton

HM Government. (2012) Industrial Strategy: government and industrial partnership. Building Information Modelling. London. HM Government

HM Government. (2013) Industrial Strategy: government and industrial partnership. Construction 2025. London. HM Government

Institution of Civil Engineers (ICE), (2015, June 30) Complete the annual BIM Heat Map survey and win a place at the ICE BIM Conference. Retrieved from https://www.ice.org.uk/news/complete-the-bim-heat-map-and-win-a-place

Institution of Civil Engineers (ICE). 2017. From Transactions to Enterprises. A new approach to delivering high performing infrastructure. London. Infrastructure Client Group, ICE.

Kemp, A. (2014, July 16) The BIM phenomenon in the infrastructure Industry. Birmingham: ICE

Khosrowshahi, F. and Arayici,Y., (2012). Roadmap for implementation of BIM in the UK construction industry. Engineering, Construction and Architectural Management, 19(6), 610 - 635

Latham, M. (1994) Constructing the team, Final report of the government/industry review of procurement and contractual arrangements in the United Kingdom construction industry. London. HMSO, Department of Environment.

Naoum, S. (2007). Dissertation Research & Writing for Construction Students. Oxford. Butterworth-Heinemann.

NBS (2017), (2017, May 23) What is IFC. Retrieved from https://www.thenbs.com/knowledge/what-is-ifc

Neuman, W. (2014) Social Research Methods - Qualitative and Quantitative Approaches (7th ed.) London: Pearson Education Inc

New Civil Engineer (NCE), (2014, January 1). Infrastructure in 2014: Why harvesting data is the new BIM. Retrieved from https://www.newcivilengineer.com/infrastructure-in-2014-why-harvesting-data-is-the-new-bim/8656981.article

Rezgui, Y., Zarli, A. and Hopfe, C.J. (2009) Editorial – Building Information Modelling Applications, Challenges and Future Directions. Journal of Information Technology in Construction, 14(7), 613-616

Rezgui, Y. and Zarli, A (2006). Paving the way to digital construction: a strategic roadmap. Journal of

Construction Management and Engineering, 132(7), 767-776

Royal Institute of British Architects (RIBA) (2012) BIM Overlay to the RIBA Outline Plan of Work. London: RIBA

Thames Water (2013) Alliance formed for 2015 to 2020 investment programme. Retrieved from www.thameswater.co.uk/media/press-releases/17101.htm

The Water Services Regulatory Authority (Ofwat), (2015) Water Companies Today. Retrieved from https://www.ofwat.gov.uk/industryoverview/today/watercompanies#wasc

The Water Services Regulatory Authority (Ofwat) and Department for Environment, Food & Rural Affairs (Defra), (2006, January 27) The development of the Water Industry in England and Wales: Ofwat Retrieved from www.ofwat.gov.uk/publications/.../rpt_com_devwatindust270106.pdf

Water Industry Forum (WIF) (2015, June 19) BIM – reducing costs in the water sector. Retrieved from http://www.waterindustryforum.com/member-services/events/wif-events/bim-reducing-costs-in-the-water-sector/

IMPLEMENTATION OF BUILDING INFORMATION MODELLING IN THE UK INFRASTRUCTURE SECTOR – A CASE STUDY

Haddy Jallow[1*], Suresh Renukappa[1], Subashini Suresh[1] and Ahmed Alneyadi[2]
[1]University Of Wolverhampton
[2] Abu Dhabi Police GHQ
email: Haddyj_04@outlook.com

Abstract

The Building Information Model concepts includes a range of IT tools supporting the collaborative processes in an organisation. This approach allows all stakeholders to have an integrated system in which editing and retrieving up to date information on shared models will become easier changing the businesses processes. This paper will be presenting a review of research on the Building Information Model in practice. The Building Information Model has been around for some time and is becoming more popular as of its mandate in the UK back in April 2016. This research is based on case studies on BIM in practice in the transport infrastructure sector. The methodology for this research is a case study on a Tier 1 contractor in the UK who are using BIM as one of their processes. A brief overview of BIM will be explained and the key findings in the research will be highlighted identifying the business value of BIM, the results will demonstrate how BIM is being practiced within the organisation and to improve design management, the challenges with the implementation of the new processes will be outlined, this paper will also show how the construction company have utilised the adoption of BIM to mitigate and manage communication issues within their projects. Research has shown that the key communication and management problems such as loss of documentation, poor communication and quality can be mitigated with the use of BIM. Finding out these challenges will allow the issues found along with the potential of BIM to be outlined and allows the conclusion that BIM is the future of construction. This research allows professionals and academics to understand the process of the Building Information Model and how it can benefit the infrastructure sector. The research will provide challenges faced by the case studies which will enable readers to overcome these challenges as they are aware of what to expect, hence finding solutions.

Keywords: Building Information Model, Communication, Engineering and Construction, Collaboration, Infrastructure.

1. Introduction

The UK economy has been growing over the years averaging at 0.6% growth in three months back in September 2018 which has been the strongest increase since the last quarter of 2016 (Ferreira, 2018). The construction industry has played a major part in the economy growth as the UK government has invested over £600 billion over the next decade on infrastructure and at least £44 billion on housing (UK Gov, 2018). On a global scale, construction projects are becoming more complex, construction project now include several stakeholders and with the rapid growth within the industry communication challenges arise. Communication can affect the quality of the design which can have an impact on project costs.

Construction projects also go through frequent design changes and these changes need to be fed back to the construction team as soon as possible to ensure projects are built to the updated and latest designs. The Building Information Model has in a major topic in the construction industry globally as benefits of its use within construction have come to light. It has been noted that BIM can provide various benefits to the construction process, from the design stage to asset management. To better understand BIM this paper presents a case study to demonstrate the key challenges faced within the project. Key communication challenges are analysed and the key lessons learned are documented. The project currently uses the Building Information Model as one of its processes, this will be investigated, and this paper will highlight how the Building Information Model is being used within the project and if there have been any challenges with the use of BIM. The paper will be split into four sections which answer the research questions:

Research question 1: How important is design management within construction projects?

Research question 2: How does BIM benefit the construction Industry and what technologies are being used in the construction industry?

Research question 3: What is the current state of BIM within the case study project and what challenges and benefits are being faced?

Research question 4: what are the future recommendation for the use of BIM within this project?

Based on the research questions, the main objective for this paper is to conduct a literature review by providing an overview of construction practices and design management within the project. The paper is structured to present the literature review answering research questions 1 and 2. Research question 3 is conducted using the case study research methodology, which will contain the practice of BIM in the construction industry, and finally research question 4 will explore the results from the case study with the finding and challenges explored this will then lead to future recommendations on this research.

2. Literature Review

2.1 Building Information Model (BIM)

In about 1957, Dr. Patrick J Hanratty, the creator of CAM (Computer Aided Manufacturing) took chance to present the AEC (Architecture, Engineering, and Construction) with the Building Information Model and this was the first the model was heard of (Mandhar & Mandhar, 2013). BIM has become more popular over the past 10 years, this is mainly because it contains a lot of benefits compared to most of the other software's. The biggest benefit of using the BIM if used from the start of the project is within the area of design development. With BIM being a 3D model, it is an ideal standard for examining the relations between a number of features of the project and also evaluating their compatibility with the local topography. Transportation Infrastructure has a long lifespan and as mentioned before with BIM being helpful with maintenance aspects, it would be a suitable match to use it with the project. BIM does not only benefit the owners, but also the contractors, architects and everyone involved in the project at hand. For the contractors, it assists with communication be being visual. At the tendering stage, it gives the contractor an opportunity to give the client a display of how they would intend to go on with the project and how he has limited some of the construction in order to get the best quality as long as best price (Smith, 2012). The software would not only benefit in the sense it could potentially win them the contract, it also provides an opportunity to have an overview of the designer's detail and challenge it if a better outcome could be achieved.

Many benefits of BIM have been documented such as reduction in project costs, saving time, improving projects communication and collaboration and project quality (Diaz, 2016). This Building Information Model also provides the means to increase design quality through detecting clashed between the different disciplines on the design prior to construction, BIM also improves the sharing of Information within the different stakeholders via a Common Data Environment (CDE), this allows the construction teams to always have access to up to date information for construction.

There are many benefits that have been recognised through the use of BIM however there are also challenges faced when implementing and adopting BIM which have been found as follows:

• *More work at the start*

As BIM would require training for the prime contractors, designers and so on, it requires a lot of effort at the beginning of the project. All of these parties need a sit down to produce a collaborative model (Carlin, 2010).

• *Programmes' ability to work with other software*

With the programmes difficulty to work with other software, the company using BIM should consider how they are going to "consolidate, interpret and utilise the increasingly mountainous volumes of data" (Mason, 2014).

• *Stakeholder's software compatibility*

For the stakeholders to have compatibility, it is not necessary for them to be using the same software platform, however it is necessary for the software being used by each stakeholder to be compatible as they would be able to exchange data and files. The issue that can arise from BIM is incompatibility between software's for these stakeholders. This however has a solution, as the IFC software programme enable compatibility between BIM and other software's (Dowhower, 2010).

Just to name a few.

BIM is a process and includes a wide range of other technologies which work together to provide more benefit to a project, this use of technologies is known as Industry 4.0 as the construction industry is going through a digitisation era.

2.2 Industry 4.0; IoT Technologies

The UK have now entered a new industrial era known as Industry 4.0, this is known as the trend towards the digitalisation and automation of the manufacturing and construction industry. Industry 4.0 comprises of various technologies including BIM to enable a digitalised environment for the construction and manufacturing industry (BCG, 2019). The results of the use of Industry 4.0 have proved to improve quality and decrease time while improving performance within a project, despite all these benefits, the construction industry have yet to integrate these technologies as well as the automotive and manufacturing engineering sectors have (BCG, 2019).

Some of the technologies linked with Industry 4.0 are mentioned below:

Cloud: The construction Industry contains a lot of data which is to be stored at all stages of construction to enable a better asset management. Loss of data during the construction stage is a big issue, having a cloud to access data and store data can increase productivity and prove profitable for an organisation (IBM, 2019).

Artificial Intelligence/Virtual Reality: Virtual reality is becoming more popular in the construction industry compare to Artificial Intelligence. With Virtual reality, the project can be view prior to its construction and its purpose can be viewed with the client and stakeholders making them confident in the project, the like of High Speed 2 railway in the UK have used this technology to show the public

(IBM, 2019).

Drones: Drones can be used for a variety of things in the construction industry, site data can be collected cutting surveying time to hours instead of days. Up-to-date and accurate site information can also be collected which can be used to check for the sites progress and productivity (Propeller, 2010).

Simulation: Simulations are becoming more popular in the construction industry, they are extensively used for plant training which allows operators to use machines at its trial period in the virtual world before using it on site (BCG, 2019).

Additive Manufacturing: The construction industry has been using Additive manufacturing, it is where products are pre-constructed off-site such as modular blocks, and then transported to site to allow for construction. This allows for complex designs to be constructed in an environment where the detail can be constructed accordingly and then placed of the site with no delays (BCG, 2019).

These are just a few of the technologies that are related to Industry 4.0, the Building Information Model is also one of the technologies linked with Industry 4.0, however BIM in cooperates some of these technologies to provide more benefits (Oesterreich & Teuteberg, 2016). Drones can be used with BIM to compare site data with the 3D model of the design to check progress. BIM Level 2 also requires a Common Data Environment (CDE) in which most companies use a cloud to store all their data.

3. Research Methodology

For this research, a combined methodology was used, for the purpose of answering research question 1 and 2, a systematic literature review was conducted to explore construction processes and identify the technologies linked with Industry 4.0 and BIM. For the purpose of answering research question 3, a case study research approach was adopted to investigate the Building Information Model in practice, identifying and analysing its use. To further this research and explore other technologies beyond BIM, semi-structured interviews were conducted within 3 projects in the UK to explore what is the current knowledge of Industry 4.0 technologies in the infrastructure sector in the UK. A triangulation strategy was adopted for this part of the research which offers the ability to explore the research topic from different perspectives allowing the research questions to be answered with a variety of data (Bekhet, 2012).

3.1 Systematic Literature Review

A systematic literature review is produced through aiming to identify an issue, evaluating the issue and integrating. This method was chosen as one of the research methods as it allows the research to address a broad range of questions hence minimising limitations to the research. A systematic literature review can be defined as:

> *"A review of a clearly formulated question that uses systematic and explicit methods to identify, select, and critically appraise relevant research, and to collect and analyse data from the studies that are included in the review. Statistical methods (meta-analysis) may or may not be used to analyse and summarise the results of the included studies"*

First, a literature review was conducted to gain a solid base of data for the context analysis, scholarly context was analysed which enabled the findings of the basics of technologies used in the construction industry and BIM, it was clear that the research had to be broadened which was conducted by using Google search with the key phrases of this research.

A wide range of sources were covered to gather a representative of the general outlook on this topic, these are listed below in order of academic quality:

- Journal articles
- UK government published reports
- Books
- Professional bodies such as the ICE (Institute of Civil Engineering)

3.2 Qualitative and Quantitative context analysis

It was clear that one form of analysis would not provide as much data as a combined methodology, within the qualitative analysis, recommendations from (Mayring, 2000) was followed:

- Preparation of the research questions
- Introduce categories of definitions
- Check categories are relatable to topic
- Interpretation of the results collected

3.3 Case Study Research

The aim of this case study research is to examine BIM in its natural settings and by employing multiple methods of data collection and obtaining data from professionals in the business, during this investigation we follow a framework strategy recommended by Robert K. Yin (Yin, 2014). Two factors are to be considered when interpreting the results. First, due to the limitation of investigated research paper from the year 2010, it cannot be guaranteed that all relevant publications have not been covered hence the research should be validated with further studies, e.g. expert interviews or empirical study. Secondly, a few of the research publications are non-peer reviewed, for example blog posts which may contain information that cannot be verified. Data collection was obtained through 15 interviews and questionnaires were handed out to 20 employees. 8 observations were held with different disciplines within the project.

Through observing the employees, key interactions between the different disciplines were recorded, important points within meetings and communication methods were recorded. During the interviews the responses were recorded and the main analysis method for the interviews was classifying the patterns and arguments. Notes were also taken during the interviews which were studied, and the document analysis method was adopted to support the findings from the data collecting methods.

3.4 Interviews

Semi-structured interviews: These generally consist of a variation of key questions that would assist in defining the areas of the topic that is of interest, it also at the same time allows the interviewer to pursue the answer in more detail which would be useful. The answers obtained from the responder are not limited hence more detail can be explored (Gill, 2008).

Unstructured: Unstructured interview do not reflect any ideas put into the research. These are generally very time consuming and are difficult to manage and participate. Lack of questions provided can prove difficult to explore the topic and subjects to talk about (Gill, 2008).

Interviewing is a method of its own, however there are a number of forms on interviews that can be undertaken to obtain results for a research (UTSA, 2015). Below are the two main forms of interviews that can be done:

Phone interviews: This form of interview is usually used if the respondent lives in another city or state. In these situations, it is critical for the investigator to be well prepared and undertake the interviews in a quiet area for the information being passed through the phone to be clear and understood.

Face to face interviews: This form of interviews needs to be scheduled before hand and the questions presented are to be in the same order for each respondent. These are preferred as the conversation can be semi-structured hence more information can be collected.

For this research, semi- structured interviews were conducted to collect data from staff in practice of the use of BIM and innovative practices within the case studies.

3.5 Limitation to this study

There were a few limitations within this study, as observations were undertaken with the with the employees, the observations were not consistent as employees attended meetings and also went onto having their data to day busy work life go ahead. This disrupted the observation process. due to the researcher being in the industry, there was also not enough time to observe the second project case study as the second project was at a distance. Travel became a limitation for this data collection process which also lead to some phone interviews to be undertaken instead of face-face interviews.

4. Results

The following section will start by providing related work to demonstrate the uniqueness of this contribution. The results are the presented as well as the findings from the case study research and finally future work and recommendations will be demonstrated.

4.1 Project description

The UK government has invested in smart motorways all over the country in the hopes of converting normal motorways with three lanes and a hard shoulder into All Lanes Running motorways. The M23 Junction 8-10 is one of the current projects which commenced construction in 2018 and is expected to last a duration of three years.

The proposed All Lane Running scheme would provide four permanent running lanes through converting the hard shoulder into a running lane and various technologies will be in cooperated to assist with safety and keep traffic moving. These technologies include installation of 26 new gantries (the existing gantries are to be demolished/ retained and upgraded where possible), which will be fitted with message signs and AMI's (Advanced Motorway Indicators, strategic signs and variable message signs. Speed limits will be displayed based on traffic conditions to allow traffic to keep flowing and CCTV cameras and loop detectors will be fitted to provide information support to a control centre. The central reserve will also be hardened, and a rigid concrete barrier will be fitted. The projects overall view can be seen in Figures 2 and 3.

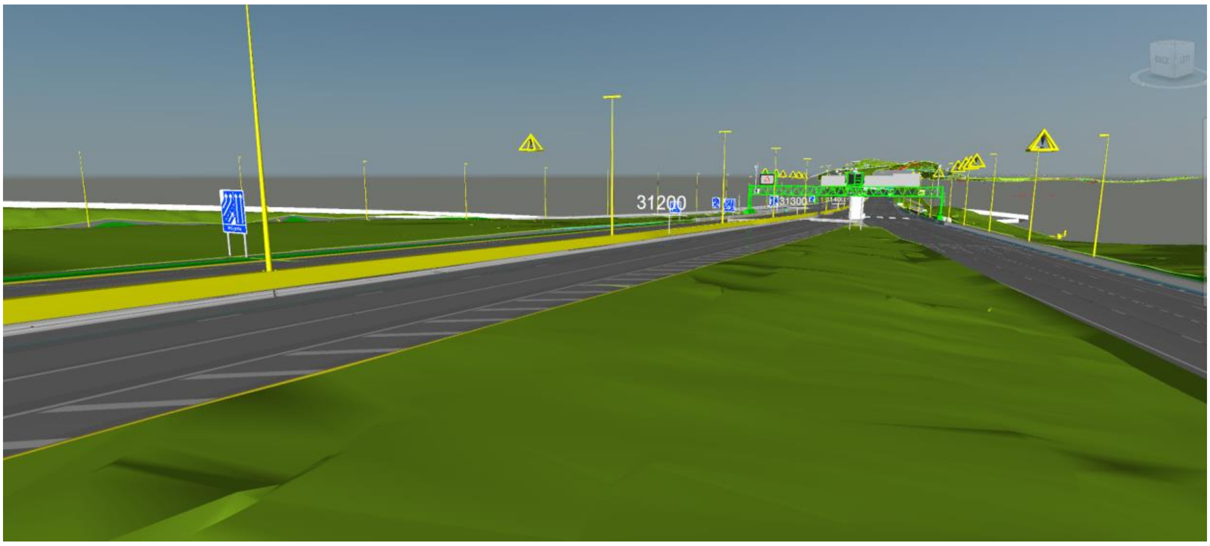


Figure 1 3D model of project; Junction 8

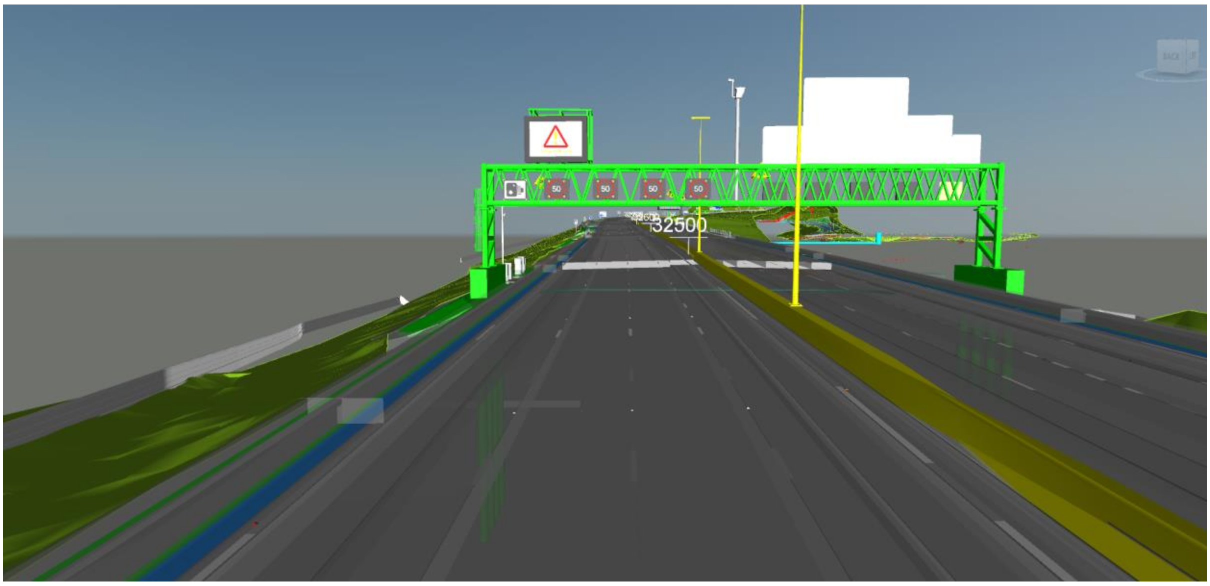


Figure 2 3D Model of project; New gantry to be constructed

The project has adopted as required by the UK government and a design 3D model was created as demonstrated in Figure 2 and Figure 3. The project comprises of three different organisations, the designers, the contractor and the client, and sub-contractors. The project has a BIM coordinator, BIM manager and BIM Coordinator of the designer's company.

4.2 Project Analysis

The following section details some of the issues being faced within the project which have been identified after the data analysis regarding the use of the Building Information Model. The discussed issues include communication tools, implementing BIM, collaboration with sub-contractors and up-skilling.

Table 1 Challenges of BIM within Case Study Project

Implication Challenge
• Acceptance: The project has adopted BIM from the start and training session are held in order to be Level 2 BIM compliant and utilise the Common Data Environment. All project information is uploaded on the contractors CDE and distributed to the relevant disciplines, however when distributed, there is a lack of responses as the disciplines do not download the updated documents form the CDE as they would grab a paper copy from team members. This is an issue because the printed copies may be previous revisions.
• Process Changes: The implementation of BIM must take place at all levels of the organisation which requires re-engineering the business practices, as most employees in the organisation have been in the industry for over 15 years, the reluctant to change the way of working is quite difficult. Training sessions are held every week to allow employees to understand the BIM Level 2 processes, however once training is completed most employees tend to revert to their old ways of working.
• Communications: Within this project there are three CDE's. The client has their own CDE which a number of people have access to and is used for Technical Queries and raising PMI's (Project Managers Instruction), the designers also have their own CDE which the client, Document Controller of contractors and themselves have access to where documents are issued, and the contractors have their own CDE which everyone has access to, as there are three CDE's with limited access for employees to two of them this can be difficult as not everyone has access to view all project information.
• Use of 3D model: the 3D model is available for use and everyone on the project has access to it, however not everyone uses it to gain the benefits it provides even though they have been trained.
• Communication Tool: the contractors CDE contains a communication tool which can be used to communicate with sub-contractors etc. however this has not used, and emails are mainly sent which can cause loss of data.

Even though there a number of issues with the use of BIM on this project, there are various benefits which BIM is providing to the project which are demonstrated in Table 2.

Table 2 Benefits of BIM to Case Study project

Implication Benefits
• 4D planning: The project has produced a 4D sequence which was requested by the client, this allowed the Planners, Operational team, CAD technician, BIM team and designers to collaborate as the design model was needed along with the programme and works sequence to produce the 4D model. The 4D sequence was produced at a section where major works were to be conducted and there were a lot of risks involved with the works. the sequence allowed the operational team to view the programme and justify that there will be enough space for the machinery and plant.
• Visualisation: The model is being used for visual purposes, to encourage the use of the model, the project has invested in a BIM station, this is a pod with an interactive monitor which consist of the model for collaboration during meetings and also consists of the CDE training videos and BIM Level 2 requirements for employees to have a look through. This has been quite a success as the pod being interactive made employees eager to play around with the model and encouraged them to attend training sessions in order to learn how to operate the software's.
• CDE: There are pitfalls with the CDE as there are three of them, however the CDE being used by the contractors takes a major role in the works, the contractors CDE is where all construction information in obtained by the operational team, however there is still to be a push for employees to adapt to obtaining the current revision of drawings uploaded.
• Asset management (Life cycle benefits): At this project, as the construction process is happening, asset data is being collected and this will be inputted into the model, the will allow the asset to be maintained in an easier way as all asset data is stored in one place and is attached to the model itself.

• Clash Detection: At the early stages of the project the model was used for clash detection between the sub-contractors and the contractors, the model was used to visualise where the proposed temporary CCTV cameras were to be placed and to check if it clashes with the proposed works, a number of clashes were found which enabled the team to move the CCTV cameras to locations where there were no clashes. this saved time of re installing the CCTV bases if the clash detection was not conducted.
• Walk through of job: A fly through of the job has been recorded by the BIM Team, which is regularly used to show stakeholders and visitors to the site and the works. Most visitors visit the site office and do not get to see the job, however with the fly through in place that is possible and reduces the safety risk as visitors do not physically go on site.

4.3 Industry 4.0 Technologies Results

Within the construction infrastructure in the UK, results show that the Building Information Model (BIM) is the most known technology within Industry 4.0. 15 employees in the industry were interviewed and 12% out of the 15 interviewees have heard of Industry 4.0. 66% however have heard of some of the technologies which are involved within Industry 4.0. the most popular technology that the interviewees revealed that they have heard of is the Virtual Reality and Augmented Reality.

Within one of the projects, the designers of the project use photo realism, Virtual reality, augmented reality and aural representation to bring life to the route of the railway line enhancing the experience and impacting the planning and consultation process. The creation of the digital version of this so to be real railway line assisted in the decision making of the project teams as it involves major works. The project has had many members of the public against it, however with the media being provided with the footage it enabled the public to get an understanding of the project and what it will look like once finished, given the opportunity to see the future enable all parties involved within the construction and design process to make better decisions at all stages of the project to date.

Despite the project utilising VR and AR, 34% of the interviewees still were unaware of these technologies associated with Industry 4.0 and 88% have not heard of the industrial revolution. The results indicate that Industry 4.0 is a majorly under researched field and awareness within the industry is very low.

4.4 Discussion

Implementing BIM

This project uses Autodesk products to produce the 3D model, AutoCAD civil 3D is used to produce the civil elements of the job and Revit is used to model the structures, i.e. bridges, gantries, etc. 84% of the design team members were familiar with the specific software, where 16% were formed of a mixture of graduates and Planning/Commercial teams. On the contractors end, the BIM team were all familiar with the software which was a benefit as the training sessions held by them with the staff members was aimed at educating other members of staff who do not understand the way of modelling and how models are created.

The implementation of BIM within this project has been semi successful, the model is available for all project staff and so is construction information within the CDE, however the process change proves to be difficult for all staff to adopt. BIM can be an efficient way to exchange design information between disciplines, which is what is being practiced on this project, but with the reluctance from employees to attend training sessions and practice what has been learned from these training sessions, the full benefits of this are not clear.

Subcontractor involvement

There are some important subcontractors on this case project, with the construction containing various details such as drainage, structures, fencing etc. the contractors have many subcontractors to assist with the construction who are experts at their field. All the design details required for construction from the subcontractors are to be shared via the CDE, however this process is not commonly used. The

CDE provides the benefit of subcontractor communications to be sent and stored for record keeping however after analysing the data from this research, 12% of the commercial team use the CDE to communication and collaborate with subcontractors. When asked the questions about the reluctance, it was noted that most of the commercial team have attended CDE training however do not regularly go on the CDE to remember all aspects discussed in the training session.

Industry 4.0 Technologies

Industry 4.0 technologies are one of the leading drivers within the digitalisation of the industry. There is a major lack of awareness with the industry on these technologies which is why the revolution has not picked up yet. As shown in the results, only 12% of the interviewees were aware of Industry 4.0 which is extremely low. Raising awareness within this topic will allow organisations to invest in the technologies associated with Industry 4.0 which and as people are unaware of the technologies more research is to be conducted within this topic to allow the industry to take the measures to allow the revolution to succeed.

5. Conclusion

This research presents a detailed study which was executed between April 2018 and January 2019 on the Building Information Model in practice on a Smart Motorway Project. The case confirms several points identified: (i) The Building Information implementation process is a tough one, it involves a lot of awareness and training to staff for level 2 to be adopted in the right manner. (ii) communication can be improved with the use of BIM, the likes of subcontractors and different disciplines in the organisation can communicate easier with the use of a CDE while all data is also stored, this however is a process that team members must undertake and adopt. (iii) BIM can contribute to communication between team members, as the results suggested the 4D sequence was a collaboration between different teams showing the planned programme of works which helped the client understand how the works are going to be undertaken.

The two most important findings in the research were that the contractor should enforce a communication framework within the organisation to ensure the use of the right BIM processes to communicate between disciplines. Secondly BIM competencies between the different disciplines should be similar and although training is being provided, more awareness on BIM would enable the organisation to raise interest on the BIM level 2 standards and processes.

References

BCG. (2019). *Embracing Industry 4.0 and Rediscovering Growth*. Retrieved from BCG: https://www.bcg.com/capabilities/operations/embracing-industry-4.0-rediscovering-growth.aspx

Bekhet, A. K. (2012). Methodological Triangulation: An Approach to Understanding Data. *Nursing Faculty Research and Publications* , 40-43.

Bibby, L. (2003). *IMPROVING DESIGN MANAGEMENT TECHNIQUES IN CONSTRUCTION.* Woking: CICE.

Carlin, E. M. (2010). *Construction Law Signal*. Retrieved November 08, 2015, from http://www.constructionlawsignal.com/by-subject/design-and-technology/the-legal-risks-of-building-information-modeling-bim/

Design Process Communication Methodology: Improving the Effectiveness and Efficiency of Collaboration, Sharing, and Understanding. (2014). *Journal of Architectural Engineering* , 1-12.

Diaz, P. (2016). Analysis of Benefits, Advantages and Challenges of Building Information Modelling in Construction Industry. *Journal of Advances in Civil Engineering*, 1-11.

Dowhower, J. F. (2010). *Utilizing BIM for Sustainable Architecture*. Retrieved November 26, 2015, from https://jdowhower.wordpress.com/chapter-5-summary-conclusions/bim-impacts-on-stakeholder-collaboration-workflows/

Ferreira, J. (2018, December 21). *United Kingdom GDP Growth Rate*. Retrieved from Trading Econimics: https://tradingeconomics.com/united-kingdom/gdp-growth

Hall, J. (2018, July 27). *Top 10 Benefits of BIM in Construction*. Retrieved from Connect & Construct: https://connect.bim360.autodesk.com/benefits-of-bim-in-construction

IBM. (2019). *How Smart id your factory*. Retrieved from IBM: https://www.ibm.com/industries/manufacturing?S_PKG=&cm_mmc=Search_Google-_-Industrial+-+Business+Operation-_-WW_EP-_-+industry++4.0++technology_Broad_&cm_mmca1=000019XS&cm_mmca2=10005255&cm_mmca7=1006685&cm_mmca8=kwd-372704782235&cm_mmca9=_k_EAIaIQobChMIw

Li, J. (2014). A Project-Based Quantification of BIM Benefits. *International Journal of Advanced Robotic Systems*.

Mandhar, M., & Mandhar, M. (2013). BIMING THE ARCHITECTURAL CURRICULA – INTEGRATING BUILDING INFORMATION MODELLING (BIM) IN ARCHITECTURAL EDUCATION . *International Journal Of Architecture (IJA), 1*(1), 1-20.

Mason, M. (2014). *Conject Blog*. Retrieved November 07, 2015, from http://conjectblog.co.uk/2014/11/6-challenges-of-bim-adoption/

Mayring, P. (2000). Qualitative Content Analysis. *Forum: Qualitative Social Research*.

Propeller. (2010). *Drones for Construction:The Beginner's Guide*. Retrieved from Propeller: http://get.propelleraero.com/guide-to-drones-construction?utm_term=construction%20drone&utm_campaign=Drones+for+Construction&utm_source=adwords&utm_medium=ppc&hsa_tgt=kwd-323604198465&hsa_grp=58974575964&hsa_src=g&hsa_net=adwords&hsa_mt=e&hsa_ver=3&hsa_ad

RODRIGUEZ, J. (2018, August 25). *Building Information Modeling (BIM) Benefits Per Profession*. Retrieved from The Balance smb: https://www.thebalancesmb.com/building-information-modeling-bim-benefits-845045

Smith, J. A. (2012, June). *Fig.net.* Retrieved November 04, 2015, from https://www.fig.net/resources/monthly_articles/2012/june_2012/june_2012_smith.pdf

Tzortzopoulos, P. (2007). DESIGN MANAGEMENT FROM A CONTRACTOR’S PERSPECTIVE: THE NEED FOR CLARITY . *eprints.hud.*, 8-15.

UK Gov. (2018, July 05). *Construction Sector Deal*. Retrieved from Gov.uk: https://www.gov.uk/government/publications/construction-sector-deal/construction-sector-deal

WaiWong, J. K. (2015). Enhancing environmental sustainability over building life cycles through green BIM: A review. *Automation in Construction*, 156-165.

XianboZhao. (2017). A scientometric review of global BIM research: Analysis and visualization. *Automation in Construction*, 37-47.

Xu, X. (2014). A framework for BIM-Enables Life-Cycle information management of construction project. *International Journal of Advance Robotic Systems*.

Yin, R. K. (2014). *Case Study Research; Design and Methods.* New Delhi: SAGE Publications.

Towards Evidence-Based BIM

Peter Johansson[1,*], Kaj Granath[2], Anahita Davoodi[1] and Géza Fischl[1]

[1]School of Engineering Jönköping University
[2]Chalmers University of Technology
*email: peter.johansson@ju.se

Abstract

Building information modeling (BIM) is widely used in the construction industry today. The development in this area constantly creates new opportunities to evaluate the properties of buildings by employing digital models. New simulation tools that can analyze a building in various ways have become available. As BIMs become more advanced, they tend to be applied earlier in the design process and can simulate the user's perception of the building in more detail. Consequently, with the development of new approaches for various properties, adequate BIM strategies that assist in depicting those properties, which can be evaluated by the emerging uses of BIM, should be developed. Accordingly, the aim of this study is to evaluate if and how an evidence-based design (EBD) approach can assist in the development of a BIM-strategy. Furthermore, we investigate how the initial steps of the EBD process, that is, finding and evaluating evidence, can be applied to decide the properties that should be identified and assessed, as well as what types of BIM uses should be rendered to represent these properties. To test such an approach, a case study on student housing was conducted in collaboration with researchers and MSc students from the Sustainable Building Information Management program at Jönköping University. Their aim was to investigate what type of properties/values should be relevant and could be rendered with BIM uses in order to evaluate these properties. In total, 15 students searched for and selected literature on relevant evidence for the student housing project and a simple framework for the levels of evidence were introduced and used to evaluate these evidences. Based on this case study, it is concluded that literature concerning different BIM uses can be found but training is needed in finding relevant scientific sources. Furthermore, working with EBD-BIM process a simplified guideline concerning the level of evidence needs to be developed.

Keywords: BIM, BIM-strategy, Evidence-based Design, Levels of Evidence

1. Introduction

Building information modeling (BIM) is becoming a well-established tool and an innovative methodology in the field of architecture, engineering, construction, and facility management (AEC/FM) (Zhou et al., 2017) and many benefits of its use have been reported e.g. (Borrmann, König, Koch, & Beetz, 2018; Eastman, 2018). The use of BIM will evolve further in the coming years (Ozturk & Yitmen, 2019; Pauwels, Zhang, & Lee, 2017) and there will be an accelerated development of new BIM uses, which will provide new ways to evaluate the properties of buildings by employing digital models. One of the promising directions of BIM is to facilitate various building simulations even in early stages of design (Eastman, 2018; Lee et al., 2012). Traditionally, design evaluation is performed manually by multiple domain-specific experts and is time consuming and expensive. With BIM, such tasks can be automated, resulting in more aspects of the building performance being evaluated in more detail and more alternatives being considered (Jalilzadehazhari, Vadiee, & Johansson, 2019; Sandberg, Mukkavaara, Shadram, & Olofsson, 2019). The development of BIM has raised a demand of strategies and plans for the application of BIM in projects. Consequently, a number of approaches to develop such strategies and plans have been proposed (CIC, 2011; Fischer, Ashcraft, Reed, & Khanzode, 2017; Kumar, 2015; Won & Lee, 2016).

One of the main tasks in these approaches is to identify the appropriate BIM uses to be adopted for the project considered. Although several structural approaches have been proposed (CIC, 2011; Kumar, 2015), there is a lack of methods relying on evidence that the BIM uses chosen will provide value to the project. This makes it possible for BIM uses to be applied for reasons other than their effectiveness, e.g., because they are profitable for the consultants.

To close this gap, a framework has been developed at Jönköping University that connects the process of light simulations and evidence-based design (EBD) (Davoodi, Johansson, Henricson, & Aries, 2017) called EBD-SIM. The term EBD has evolved from other disciplines, in particular, medicine, which has used an evidence-based model to guide decisions and practices in their fields. The most widely accepted definition of Evidence-Based Medicine (EBM) was introduced by Sackett et al. (Sackett, Rosenberg, Gray, Haynes, & Richardson, 1996). Hamilton and Stichler (Stichler & Hamilton, 2008) adopted this definition to the field of the built environment, as follows:

“Evidence-based design is a process for the conscientious, explicit, and judicious use of current best evidence from research and practice in making critical decisions, together with an informed client, about the design of each individual and unique project.” (p.3)

Interest in EBD has been growing extensively since Ulrich’s publication (Ulrich, 1984) addressed the effect of views of nature on patients (Zhang, Tzortzopoulos, & Kagioglou, 2016). In the building industry, EBD has been applied mainly to the design of healthcare facilities, even though, due to the flexibility of this method, it can be adopted by other types of buildings such as offices, schools, sports facilities, etc. (Hamilton & Watkins, 2009; Muszynski, 2009). Proponents of EBD claim that it can help to enhance outcomes throughout all phases of design. As highlighted in the abovementioned definition, EBD is a process and it is impossible and not recommended to see the best available evidence as a fixed and static guideline to support design decisions (Hamilton & Watkins, 2009). Collectively, the EBD method is an evolutionary process that continuously improves and builds on previously generated and published evidence.

There are a number of EBD-frameworks described in the literature and a literature study together with an investigation of the different frameworks can be found in (Davoodi et al., 2017). The frameworks can be categorised into three types: 1) conceptual frameworks about EBD processes in general, 2) frameworks that strengthen EBD by integrating knowledge from other disciplines, and 3) frameworks based on EBD in a specific domain (Davoodi et al., 2017). Davoodi et al. (2017) found that the frameworks of type 1 was most suitable for the development of EBD-SIM due to the need of a general conceptual framework when integrating simulations. Two literature references ((Malone et al., 2008) and (Hamilton, 2003)) describe a conceptual framework (Type 1) illustrating an EBD process in ‘general’. Hamilton et al. (Hamilton, 2003) proposed a four-level conceptual model of evidence-based design practice wherein each subsequent level increases in research rigour. The focus of the first and second level is for gathering, analysing, assessing, and generating evidence, and the two next levels deal with how to share the newly generated evidence.

The framework developed by the Center for Health (2015) was identified as the most suitable for integration with computational modeling because it gives a holistic picture of the EBD process by breaking it down into eight steps involved in different stages of construction projects (see Figure 1). This makes it possible to investigate the integration of computational modeling in each step of the EBD process. The aim of the selected EBD framework was to integrate EBD into different stages of a typical building design process. The Centre for Health Design (CHD) EBD framework contains eight steps for: (1) definition of key goals and objectives; (2) finding sources with relevant evidence; (3) critical interpretation of relevant evidence; (4) creation and innovation of EBD concepts; (5) development of a hypothesis; (6) collection of baseline performance measures; (7) monitoring of design and construction implementation; and (8) measurement of post-occupancy performance results. It is important to note that, while the steps appear linear, the EBD process is fluid and the steps can be repeated in different phases of the project, and the EBD is a continuous process, as shown in Figure 1. The CHD framework has influenced the work by Joseph et al., (2014), who strengthened the EBD knowledge base by developing standardized post-occupancy evaluation (POE) tools.

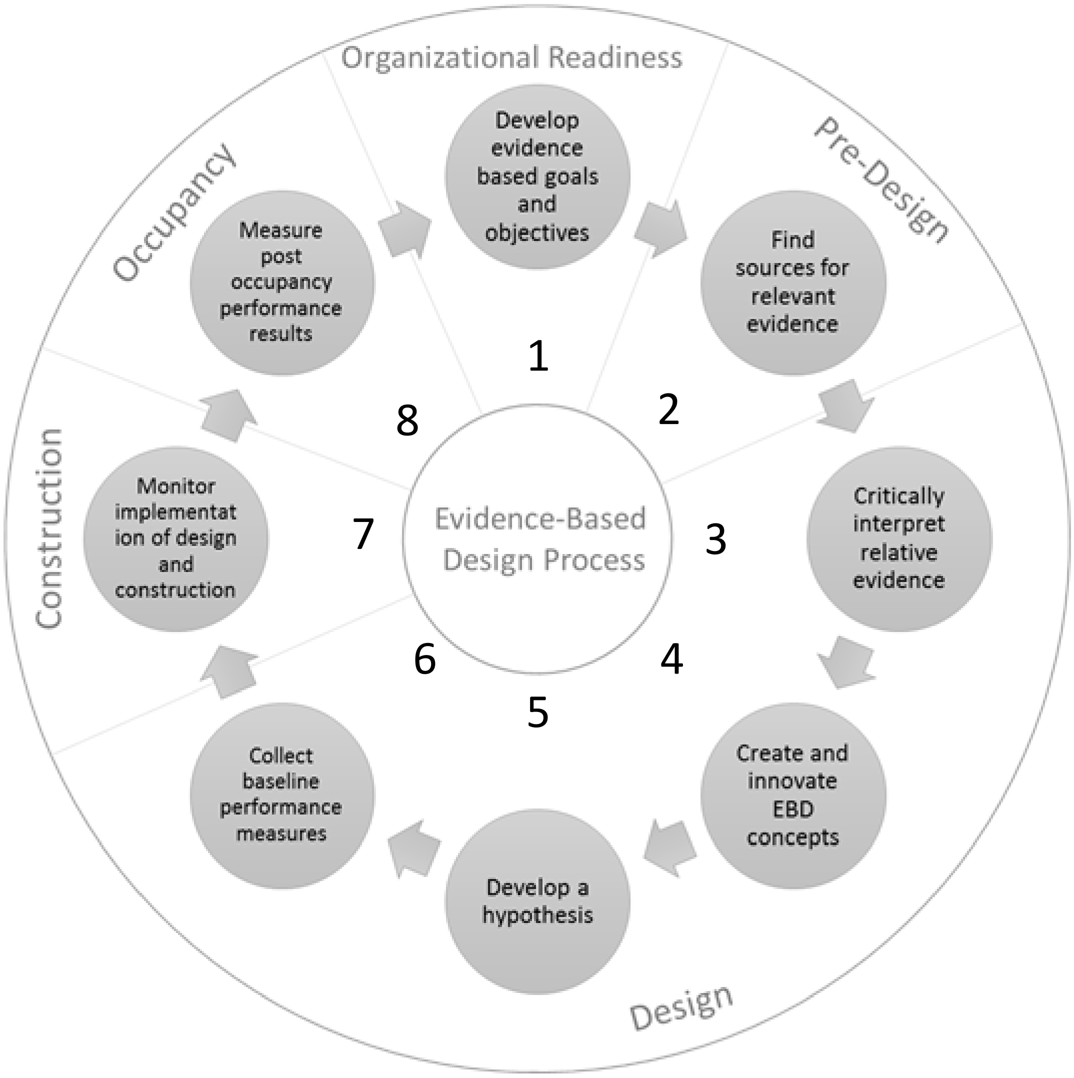


Figure 2: The EBD process ((Joseph et al., 2014)

The aim of this study is to further develop the EBD-SIM framework toward a framework for evidence-based BIM (EBD-BIM).

It was noticed that one of the barriers in adopting EBD in the building design process with computational modeling is the limited amount of evidence sources (including both literature and example projects) that can be readily used by the design practitioners (Davoodi et al., 2017). To investigate this barrier, we decided to investigate the reachability of evidence sources in the area of BIM, focusing on the first two CHD's steps: (1) definition of key goals and objectives and (2) finding sources with relevant evidence. There are also two similar tasks connected to the development of a BIM strategy: 1) to identify the appropriate BIM uses and 2) to find sources with evidence relevant for these BIM uses.

2. Method

A case study on student housing was conducted with MSc students from the Sustainable Building Information Management program at Jönköping University with the aim of investigating the initial CHD's steps, described above, for a building project of a student residence on a plot near the university. In total, fifteen students, divided into five groups, searched for and selected literature on relevant evidences. The students have received their bachelor's degree from different universities in Europe, Afrika and Asia and they before this case-study got an introduction to literature reviews by the personal at the university library and had conducted two exercises containing search for scientific literature.

The students preformed two tasks connected to values:

V1) definition of key goals and objectives;

V2) finding of sources for relevant evidence;

and two tasks connected to BIM uses:

B1) to identify the appropriate BIM uses and

B2) to find sources with evidence relevant for these BIM uses

The tasks were performed in similar manner by primarily searching for evidences in the literature. To help them starting this process the researchers gave lectures concerning regulations and values relevant to student housing. Having this the students started to search for literature concerning values, to answering the value tasks V1 and V2. After that they started to perform the tasks related to BIM uses, B1 and B2. This was mainly performed by conducting a literature search having the values as input. This exercise resulted in a report, from each group, that documented 10-20 values and related BIM uses together with a discussion concerning the sources of evidences found. The reports were assessed by the researchers and the level of evidence (LOE) were evaluated.

In the planning of this case-study, some guidelines for the LOE were investigated (Pati, 2011) and, although these guidelines reduced the need for scientific rigor, validity, and reliability, it was concluded that they were still too complicated for the students to follow. Instead, the researchers developed a simplified "levels of evidence" framework to evaluate the evidence. The levels were as follows:

1. Common understanding
2. Stated by a company
3. Scientific papers
   a) Can be performed
   b) Verified (measurable value)
   c) Validated (value is received (POE))

The first and lowest level was named "**Common understanding**" meaning that the only evidence provided is arguments confirming that the BIM use considered provides values to the project. The second level was named "**Stated by a company**," meaning that companies have stated, mostly on their websites, that the BIM use considered provides value. The third and last level, named "**Scientific papers**," indicates evidence found in scientific papers. In this category three sub levels were provided. Scientific papers that focused on showing a possibility, an exploratory study, was categorized in the **3a** level named "Can be performed". In the second sublevel **3b** the scientific papers show a BIM use but also indicate how the result form this BIM use can be verified. An example of this is a paper describing light simulations and how these simulations can be verified by measuring illuminance in the final building. At the third sublevel, **3c**, the scientific papers should also include a Post Occupancy Evaluation (POE) that validate that the expected value was also received.

As an incentive for the students to find evidences on a high level the grading of the exercise included the LOE they provided.

3. Result

Table 1 show the result from the students' efforts in number.

Table 1: Result from all the groups

Group	1	2	3a	3b	3c	SUM
1	0	2	3	2	8	15
2	1	2	10	0	3	16
3	7	7	1	0	0	15
4	0	11	0	1	0	12
5	0	3	4	2	2	11
Sum:	8	25	18	5	13	69

As can be seen from *Table 1* the different groups documented between 11 to 16 different values/BIM-uses. The number of values/BIM-uses documented were 69 in total. The result from the evaluation of the sources of evidence in the documentation, concerning the LOE, is shown in the different columns. The students found scientific papers for 36 (52%) of the values/BIM uses. 18 of these were in the category "Can be performed", five in the category "Verified (measurable value)" and 13 in the category "Validated (value is received (POE))". For the other 33 (48%) values/BIM uses the sources of evidence were categorized as "Stated by a company" 25 (36%) or "Common understanding" 8 (12%).

Table 2 contains the result for the of the student groups with the highest level of evidence (LOE).

Table 2: Result from Group 1

Goal/Value	**BIM Use/Software**	**LOE**
Adequate size of rooms	Design authoring (Audit and Analysis tools): Solibri	3c
Organized site layout	Site Utilization Planning: Infraworks FormIt	3c
Adequate lighting	Daylight analysis: Velux Lighting analysis: Dialux	3c
Adequate indoor temp	Energy simulation: IDA ICE	3c
Good acoustic quality	Noise simulation tool: EASE focus	3c
Air quality	Wind analysis: CFD Autodesk	3c
Indoor recreation and soc area	space management Model checking: Solibri	3c
Building maintenance	Building (Preventative) Maintenance Scheduling	3b
Cost affordability	Cost Estimation (Quantity Take-Off): VICO, RIBiTWO	2
Energy performance	Facility Energy Analysis: IDA ICE	2
Security system	Design Review: Solibri	3a
Accessibility	Design Review: SolibriSolibri	3b
Internal housing facility	Design Review: dRofus	3a
Fire safety	Design Review: Solibri	3c
Zero emission building	Sustainability (LEED) Evaluation: Revit	3a

As can be seen from *Table 2* the group found 15 values/BIM-uses and in the LOE-column the result from the evaluation concerning the level of evidence is shown. From this column it can be concluded that the group found scientific papers for 13 (87%) of the values/BIM uses. Three of these were in the category “Can be performed”, two in the category “Verified (measurable value)” and eight in the category “Validated (value is received (POE))”. For the other two values/BIM uses the sources of evidence were categorized as “Stated by a company". No values/BIM uses had the sources of evidence categorized as “Common understanding ".

Table 3 show the result from the other groups.

Table 3: Result from Group 2, 3, 4 and 5

Group 2			Group 3		
Goal/Value	**BIM Use/Software**	**LOE**	**Goal/Value**	**BIM Use/Software**	**LOE**
Room size	Solibri	3a	Access to public transport	ArcGis, Grass Gis, Rhino, Google Map Transit	2
Internal housing asset	dRofus	3a	water and wastewater	MagiCAD, BIM 360 OPS	2
Accessibility	Solibri	3a	materials quality and durability	Tekla, Rhino, 3D Max + Revit	2
Parking space management	Park CAD 4.0	2	entertainment and sport environment	dRofus	1
Residential critical areas	dRofus	3a	energy efficiency	MagiCAD, Energyplus	1
Interior and exterior appearance	Lumion 8	3a	indoor air quality	Energy Plus	1
Internet facility	iBwave design	3a	accessibility	SMARTreview APR	1
Space cost	VICO Office	3a	safety	solibri	2
Safety	MassMotion Software	3c	visual comfort	Velux, Light analysis Revit , Radiance	3a
Maintenance scheduling	ARCHIBUS v.23	1	space comfort	solibri, dRofus	2
Reachability	ArcMap	3a	accommodation costs	autodesk quantity takeoff,	2
Acoustic comfort	EASE FOCUS	3a	acoustics	Unclear	1
Visual comfort	Velux Daylight Visualizer IDA ICE	3c	furnishing	Unclear	1
Thermal comfort	IDA ICE	3c	green area	various kinds of gis tools	2
Indoor air quality	CFD	3a	smart building	Unclear	1
Wastewater management	Revit MEP Plugin	2			

Group 4			Group 5		
Goal/Value	**BIM Use/Software**	**LOE**	**Goal/Value**	**BIM Use/Software**	**LOE**
Optimal site location	SITE ANALYSIS – LOCATION	2	Cost	Cost Estimation (Quantity Take Off)	3a
SUSTAINABILITY EVALUATION	SUSTAINABILITY EVALUATION	2	Conductive Location	Site Analysis	2
SPACE COSTS	COST ESTIMATION	2	Fire Safety	Disaster Planning	3a
THERMAL COMFORT	SUSTAINABILITY EVALUATION	2	Sanitary Quality	BIM Use: Building (Preventative) Maintenance Scheduling & Asset Management	3b
Light efficiency	LIGHTING ANALYSIS	2	Acoustic Comfort	Engineering Analysis (Structural, Lighting, Energy, Mechanical, Another) & Code Validation.	3a
Sizing acoustic protection	ACOUSTICS	2	Energy Use and Performance	Facility Energy Analysis	3c
ACCESSIBILITY	PROGRAMMING	2	Visual Comfort	Lighting Analysis	3a
AIR QUALITY	BUILDING SYSTEM ANALYSIS	2	Thermal Comfort	Use Sustainability / LEED Evaluation	3c
SAFETY	DISASTER PLANNING	2	Internal Living Space Wide Area	Space Management and Tracking	2
MAINTAINABILITY	ASSET MANAGEMENT	2	Having Privacy Occupants	Space Management and Tracking	2
ENERGY CONSUMPTION	FACILITY ENERGY ANALYSIS	2	Accessibility	Space Management and Tracking	3b
SPACE EFFICIENCY	SPACE MANAGEMENT & TRACKING	3b			

It can be seen in *Table 3* that the different groups focused on different LOE. Group 3 and Group 4 found just one scientific paper for the values/BIM uses. Group 3 also used “Common understanding " as their main sources of evidence while Group 4 used sources of evidence categorized as “Stated by a company" mainly. Group 2 and Group 5 found sources of evidence in different categories. In this table the terminology is directly copied from the reports of the students. This makes it possible to see the variety of terminology used by the different groups, both for Goal/Value and for BIM Use/Software. It also shows the difference in the type of terminology used, e.g. that some of the groups just give the name of the software in the BIM Uses/Software column and other groups the BIM use.

4. Discussion and Conclusion

It was observed in an earlier study by Davoodi et al. (2017) that one of the barriers in adopting EBD in the building design process with computational modeling is the limited amount of evidence sources (including both literature and example projects) that can be readily used by the design practitioners. Accordingly, we developed a case-study for MSc students at the Sustainable Building Information Management program at Jönköping University, wherein they were asked to find literature needed to conduct the first two steps in the CHD framework. A little more than half of the sources found by the students were scientific papers (36 of 69, 52%) and a little less than half (33of 69, 48%) were considered as nonscientific sources. The difference between the groups results of finding evidences were noticeable and the percentage of sources being scientific papers differed from 7% to 87% between the groups. It is rather obvious that two of the groups focused on sources of evidence in the two lowest categories. *Table 2* shows the result from the group that had the highest level of evidence and this group did not find scientific papers for two of the value/BIM use. Having the values/BIM-uses for these two it is rather obvious for the researchers that there are scientific papers available also concerning these values/BIM uses. From *Table 3* it is rather obvious that two of the groups focused on sources of evidence in the two lowest categories. There was also a large variation between students regarding the sources of evidence found, only three of the students had scientific papers for all the values/BIM uses and eight of the students found scientific papers for more than half of the values/BIM uses which they were responsible for. This indicates that scientific literature concerning different BIM uses can be found but the students on master level still show limited training in finding relevant scientific sources. The same can probably also be stated for most people working in the AEC/FM industry and to be able to implement an EBD-BIM process training is needed. However, in the same way as some of the students went through this extra effort to obtain a higher grade, an incentive is needed to establish this as a way of working in professional practice.

In the planning of the case-study, some guidelines for the level of evidence were investigated (Pati, 2011) and, although these guidelines have been simplified regarding required level of scientific rigor, it was concluded that they were still too complicated for the students to follow. From the results, it can be concluded that, working with EBD-BIM process, a simplified guideline concerning the level of evidence needs to be developed.

The students were introduced to literature containing terminology of values (Annerstedt et al., 2012) and BIM uses (CIC, 2011),yet the result shows a great variety of terminology used by the different student groups. An explanation is that the literature found by the students contains a variety of terminology and students have not understood the difference between value, BIM use and software and the importance of using these standard terminologies. For EBD-BIM to be practically useful the use of classification/standard terminology concerning values and BIM uses is needed be disseminated.

References

Annerstedt, J., Mouritsen, J., Huovila, P., Huovila, A., Juha Hyvärinen, & Mäkeläinen, T. (2012). *D2 Value models in building and real estate industry*. Retrieved from

Borrmann, A., König, M., Koch, C., & Beetz, J. (2018). *Building Information Modeling Technology Foundations and Industry Practice*: Cham : Springer International Publishing : Imprint: Springer.

Center for Health, D. (2015). *An introduction to evidence-based design : exploring healthcare and design* (3. ed.. ed.). Concord, Calif.: Concord, Calif. : The Center for Health Design.

CIC, C. I. C. R. P. (2011). *BIM Project Execution Planning Guide – Version 2.1*. Retrieved from University Park, PA, USA:

Davoodi, A., Johansson, P., Henricson, M., & Aries, M. (2017). A Conceptual Framework for Integration of Evidence-Based Design with Lighting Simulation Tools. *Buildings, 7*(4), 82. Retrieved from http://www.mdpi.com/2075-5309/7/4/82.

Eastman, C. M. (2018). *BIM handbook : a guide to building information modeling for owners, managers, designers, engineers and contractors* (Third edition. ed.): Hoboken, New Jersey : Wiley.

Fischer, M., Ashcraft, H., Reed, D., & Khanzode, A. (2017). *Integrating Project Delivery*: John Wiley & Sons.

Hamilton, D. K. (2003). The four levels of evidence-based practice. *Healthcare Design, 3*(4), 18-26.

Hamilton, D. K., & Watkins, D. H. (2009). *Evidence-based design for multiple building types*: John Wiley & Sons.

Jalilzadehazhari, E., Vadiee, A., & Johansson, P. (2019). Achieving a Trade-Off Construction Solution Using BIM, an Optimization Algorithm, and a Multi-Criteria Decision-Making Method. *Buildings, 9*(4), 81. Retrieved from http://www.mdpi.com/2075-5309/9/4/81.

Joseph, A., Quan, X., Keller, A. B., Taylor, E., Nanda, U., & Hua, Y. (2014). Building a knowledge base for evidence-based healthcare facility design through a post-occupancy evaluation toolkit. *Intelligent Buildings International, 6*(3), 155-169. doi:10.1080/17508975.2014.903163

Kumar, B. (2015). *A Practical Guide to Adopting BIM in Construction Projects*: Whittles.

Lee, J.-K., Lee, J., Jeong, Y.-s., Sheward, H., Sanguinetti, P., Abdelmohsen, S., & Eastman, C. M. (2012). Development of space database for automated building design review systems. *Automation in Construction, 24*(Supplement C), 203-212. Retrieved from http://www.sciencedirect.com/science/article/pii/S0926580512000441. doi:https://doi.org/10.1016/j.autcon.2012.03.002

Malone, E., Harmsen, C., Reno, K., Edelstein, E., Hamilton, D., & Salvatore, A. (2008). An introduction to evidence based design: exploring healthcare and design (EDAC Study Guide Series, Vol: 1). *Concord, CA: The Center for Health Design*.

Muszynski, L. (2009). Studies Link Green Design, Occupant Productivty. Retrieved from http://www.facilitiesnet.com/Green/article/Studies-Link-Green-Design-Occupant-Productivty--11283?source=part

Ozturk, G. B., & Yitmen, I. (2019). Conceptual Model of Building Information Modelling Usage for Knowledge Management in Construction Projects. *IOP Conference Series: Materials Science and Engineering, 471*, 022043. Retrieved from http://dx.doi.org/10.1088/1757-

899X/471/2/022043. doi:10.1088/1757-899x/471/2/022043

Pati, D. (2011). A Framework for Evaluating Evidence in Evidence-Based Design. *HERD: Health Environments Research & Design Journal, 4*(3), 50-71. doi:10.1177/193758671100400305

Pauwels, P., Zhang, S., & Lee, Y.-C. (2017). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction, 73*, 145-165. Retrieved from http://www.sciencedirect.com/science/article/pii/S0926580516302928. doi:https://doi.org/10.1016/j.autcon.2016.10.003

Sackett, D. L., Rosenberg, W. M., Gray, J. M., Haynes, R. B., & Richardson, W. S. (1996). Evidence based medicine: what it is and what it isn't. In: British Medical Journal Publishing Group.

Sandberg, M., Mukkavaara, J., Shadram, F., & Olofsson, T. (2019). Multidisciplinary Optimization of Life-Cycle Energy and Cost Using a BIM-Based Master Model. *Sustainability, 11*(1), 286. Retrieved from http://www.mdpi.com/2071-1050/11/1/286.

Stichler, J. F., & Hamilton, D. K. (2008). Evidence-based design: What is it? *HERD: Health Environments Research & Design Journal, 1*(2), 3-4.

Ulrich, R. (1984). View through a window may influence recovery. *Science, 224*(4647), 224-225.

Won, J., & Lee, G. (2016). How to tell if a BIM project is successful: A goal-driven approach. *Automation in Construction, 69*, 34-43. Retrieved from http://www.sciencedirect.com/science/article/pii/S0926580516301029

http://ac.els-cdn.com/S0926580516301029/1-s2.0-S0926580516301029-main.pdf?_tid=de6182dc-d18d-11e6-9b6f-00000aacb35f&acdnat=1483431973_24ae1e093311e577d877cf0f91d080ca. doi:http://dx.doi.org/10.1016/j.autcon.2016.05.022

Zhang, Y., Tzortzopoulos, P., & Kagioglou, M. (2016). *Evidence-Based Design in Healthcare: A Lean Perspective With an Emphasis on Value Generation.* Paper presented at the Proceedings of the 24th Annual Conference of the International Group for Lean Construction.

Zhou, Y., Ding, L., Rao, Y., Luo, H., Medjdoub, B., & Zhong, H. (2017). Formulating project-level building information modeling evaluation framework from the perspectives of organizations: A review. *Automation in Construction, 81*, 44.

Development of a BIMAsset Maturity Model

Mustapha Munir[1], Arto Kiviniemi[1], Stephen W Jones[2], Stephen Finnegan[1] and Pedro Mêda[3]

[1]School of Architecture, University of Liverpool
[2]School of Engineering, University of Liverpool
[3]Construction Institute, CONSTRUCT – Gequaltec, Faculty of Engineering University of Porto
[*]email: mmunir@liverpool.ac.uk

Abstract

This paper presents a BIMAsset Maturity Model (BAMM) which demonstrates how asset owners can appraise the maturity of their organisations in relation to their capability of realising Building Information Modelling (BIM) business value in Asset Management (AM). The study aims to develop and enhance the understanding of asset owners in relation to techniques of appraising key business processes that help derive BIM business value during asset operations. The study utilises a qualitative multi-case study strategy to develop a maturity model that is specific to the domains of BIM, AM and value realisation management. Also, this study adopts an inductive approach using semi-structured interviews to collect data. Furthermore, an expert panel in the form of a focus group is utilised to validate the BAMM. This study finds that the ability of asset owners to derive BIM business value during asset operations has maturity implications in relation to certain key business processes. Furthermore, the study reveals that business value can be derived by the asset owner if organisational processes such as BIM strategy, contract management, lifecycle management, maintenance management, work-order management and value realisation management are effectively executed and continuously improved to an advanced stage of maturity. An important contribution of the paper is that it presents a novel approach for evaluating owner-operator organisations using the BAMM from two perspectives; AM business processes (BIM strategy, contract management, lifecycle management, maintenance management, work-order management and value realisation management); and BIM governance dimensions (people, process and technology).

Keywords: BIM, BIMAsset, AM, Value realisation, Maturity.

1.0 Introduction

Building Information Modelling (BIM) is one of the recent disruptors of the Architecture, Engineering and Construction (AEC) industry (Aranda-Mena, Crawford, Chevez, & Froese, 2009). Asset owners are faced with BIM implementation challenges and maturity models are tools meant to simplify those processes. Generally, maturity models assume that organisational change or process development is achieved in distinct stages whilst capturing capability maturity at particular periods as well as positioning an organisation in line with defined best practices and providing the right solutions for change (Blommerde & Lynch, 2016). BIM in this study is defined as '*a set of interacting policies, processes and technologies producing a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle*' (Succar, Sher, & Aranda-Mena, 2007). The use of BIM enables asset managers to perform these activities and have the ability to generate more reliable information for their daily work (Wijekoon, Manewa, Ross, & Marsh, 2016). Patrick, Munir & Jeffrey (2012) define a BIMAsset as '*the combination of BIM technologies together with the updated facility information, models, associated links and references in an interoperable structure to be handed over to clients at the point of practical completion or at the point of sale*'. A BIMAsset is developed through the integration of accurate data of a facility over its entire lifecycle. This study adopts the term 'BIMAsset' in developing a maturity model that focuses on the domains of BIM, Asset Management (AM) and value.

Research to date has focused on BIM-based maturity models that mostly address the design and construction phases (Bew & Richards, 2008; Succar, 2010; Liang, Lu, Rowlinson, & Zhang, 2016) and there is a lack of maturity models that are specific to AM, BIM and value realisation management. There is a need to develop the understanding of asset owners in terms of the capability of their organisations in implementing BIM in AM because the benefits realised by asset owners from BIM in the operations and use phase has been marginal due to the lack of organisational synergy between people, processes and systems (Bosch, Volker, & Koutamanis, 2015). Hence, the rationale for this study.

This paper is part of a study aimed at investigating the business value of BIM in AM. The study develops the BIMAsset Maturity Model (BAMM) with the aim of providing a tool that will assist asset managers in appraising organisational maturity of BIM-based AM processes in relation to the tendency of realising BIM business value. In this paper, the BAMM is presented and its constituent elements are reviewed including its application.

1.1 Maturity Models in the AEC Industry

Maturity models originate from the software industry which are aimed at increasing productivity and reducing defects through continuous improvement of organisational practices. Generally, most maturity models are based on the Capability Maturity Model (CMM), which was developed in response to poor project performance (SEI, 1994; SEI, 2006; Blommerde & Lynch, 2016). A maturity model facilitates the easy distinction between mature and immature processes in terms of an organisational approach to business processes (Sarshar *et al.*, 2000). The maturity levels indicate a scale for evaluating the capability of individual processes in an organisation. This indication helps an organisation to establish self-knowledge of its current process maturity and support continuous improvement. Despite the large number of maturity models available in literature, their objectives are highly similar.

Researchers have proposed a number of maturity models that are applicable to the AEC industry. One is the Structured Process Improvement for Construction Enterprises (SPICE) model (Sarshar *et al.*, 2000). The SPICE model presents various levels of maturity as enablers to help construction companies to improve their processes. Another is Construction Supply Chain Management (CSCM), which focuses on the management of information, costs and workflows in a construction project (Vaidyanathan and Howell, 2007). The CSCM aims to remove inefficiencies and improve operational excellence in the construction supply chain. Similarly, the Portfolio Programme and Project Management Maturity Model (P3M3) is a framework that organisations can use to assess current performance, enhance efficiency, improve project success and achieve value for money from project and programme procurements (OGC, 2010). Furthermore, Kwak & Ibbs (2002) present a Project Management Process

Maturity (PM)² Model, which aims to integrate project management maturity models, processes and practices in order to improve effectiveness. However, the above maturity models are too generic and are not specific to BIM nor AM.

The National Institute of Building Sciences (NIBS) proposes an Innovation Capability Maturity Model (I-CMM) that is aimed at improving planning, design, construction, operation and maintenance processes using a well-established building information model (McCuen, 2008). The I-CMM determines the maturity of a building information model against a set of criteria, of which there are ten maturity levels and eleven areas of interest (NIBS, 2007). Similarly, Succar (2010) proposes a BIM Maturity Index (BIMMI), which includes defined levels that signify the evolutionary development of BIM governance dimensions at the organisational level. The BIMMI is based on the CMM and has five stages; Ad-hoc, Defined, Managed, Integrated and Optimised. Although the above maturity models are specific to BIM, they lack applicability in relation to AM and value realisation management processes. Hence, the need to develop a maturity model that addresses BIM on one hand and AM processes on the other and in appraising both from the perspective of value realisation for the asset owner.

2.0 Methodology and Research Questions

2.1 Research Question

This study aims to provide a model that will aid asset managers in evaluating organisational maturity in relation to BIM business value in an AM system. The paper seeks to provide a theoretical rationale for the development of a framework that is focused on organisational maturity in relation to BIM, AM and value realisation management. The study aims to address the following research question:

- How can an asset manager appraise organisational maturity in relation to BIM business value realisation during asset operations?

2.2 Research Methods

The study utilises a multi-case study strategy to investigate real-life phenomenon in relation to key business processes that drive BIM business value in AM (Yin, 2003). This study is conducted in two phases; literature review and case study. The literature review phase helped in the identification of significant BIM governance factors such as people, process and technology. Furthermore, the case study helped to identify key business processes such as BIM strategy, contract management, lifecycle management, maintenance management, work-order management and value realisation management. These factors were used as key elements for analysis during model development. Semi-structured interviews are utilised to collect data from the case studies. A total of four case studies were investigated, with one interview conducted for each case. However, this paper focuses on the presentation of the BAMM. The results of the case studies will be reported in future work. The methodological process is shown in Figure 1.

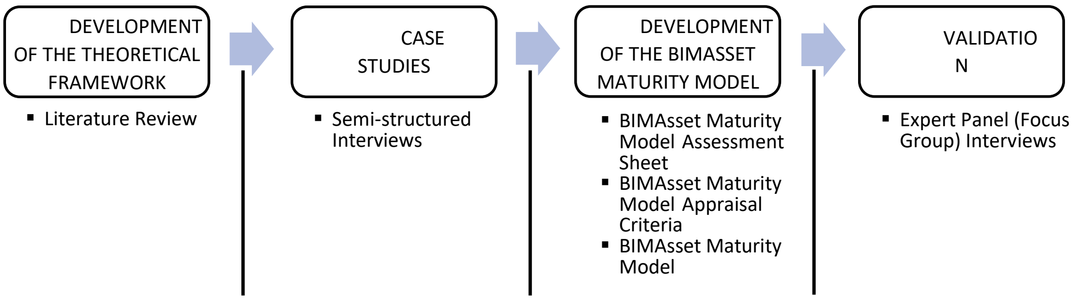


Figure 1: Methodological process

Furthermore, an expert panel in the form of a focus group interview was conducted to validate the BAMM. The criteria utilised in assessing the model's validity are: fruitfulness, prudence, quantification, scope, progressiveness, internal consistency and external consistency (Proctor & Capaldi, 2006). Data analysis from the focus group shows that 100%, 83%, 83%, 67%, 100%, 100% and 67% agree that the BAMM satisfies the above validation criteria respectively.

2.3 BIMAsset Maturity Model (BAMM) Appraisal Criteria

This study presents the BAMM tool for assessing maturity in owner-operator organisations. A number of studies have utilised a similar approach in developing maturity models (SEI, 1994; Sarshar, et al., 2000; SEI, 2006; Succar, 2010). This study utilises the five stages of BIM maturity as proposed in the BIMMI (Succar, 2010). They are, Ad-hoc, Defined, Managed, Integrated, and Optimised, which are allocated a scale of 1 – 5 points. Furthermore, the BAMM tool takes into perspective aspects of BIM governance within organisations. Hence, People, Process and Technology are added to the model and are given equal weightings (Bosch *et al.*, 2015; Prodan, Prodan & Purcarea, 2015; Alreshidi, Mourshed & Rezgui, 2017). In the context of the BAMM tool, the BIM governance dimensions are referred to as functional drivers. Furthermore, from the case study interviews, the vital BIM-based business processes in relation to value realisation in AM are referred to as activity systems. These two elements are established as the main focus of analysis. The key activity systems are BIM strategy, contract management, lifecycle management, maintenance management, work-order management and value realisation management. The BAMM appraisal criteria are described in Appendix A (via https://drive.google.com/file/d/1NFSbVfrnThWBIgohi-znN4XXjaOU8Cyw/view?usp=sharing) and the assessment sheet is shown in Figure 2. The total score from this sheet (Figure 2) qualifies the maturity level of the organisation in Figure 3.

ORGANISATIONAL MATURITY ASSESSMENT SHEET								
S/ NO	DESCRIPTION		COMPANY NAME					
			1	2	3	4	5	
1	BIM STRATEGY							
	A. People							
	B. Process							
	C. Technology							
2	CONTRACT MANAGEMENT							
	A. People							
	B. Process							
	C. Technology							
3	LIFECYCLE MANAGEMENT							
	A. People							
	B. Process							
	C. Technology							
4	MAINTENANCE MANAGEMENT							
	A. People							
	B. Process							
	C. Technology							
5	WORK-ORDER MANAGEMENT							
	A. People							
	B. Process							
	C. Technology							
6	VALUE REALISATION MANAGEMENT							
	A. People							
	B. Process							
	C. Technology							
	TOTAL SCORE		NUMERICAL VALUE					

Figure 2: BAMM Assessment Sheet

2.3.1 Activity Systems and Functional Drivers

From the case study interviews, the activity systems are acknowledged to have a vital impact on business processes performed by asset managers in order to be able to derive BIM business value. The scoring of each activity system from the dimensions of people, process and technology considered the following organisational measures in developing the BAMM appraisal criteria (Appendix A):

- BIM Strategy: Organisational BIM approaches; change management; performance management; stakeholder management; organisational policy for utilising BIM-based processes; and definition of specific organisational needs from BIM processes.
- Contract Management: Performance monitoring; invoice tracking; checking compliance; and tendering.
- Lifecycle Management: Organisational BIM standards covering asset development stages; data integration across asset development phases; process standardisation; technological capability; and human inclusion.
- Maintenance Management: Organisational culture of utilising BIM in reactive, preventive, predictive, proactive and passive maintenance-based practices.
- Work-order Management: Organisational task management protocols; process standardisation and workflows; identification of user characteristics; definition of individual and organisational data needs; automated cost estimates and invoicing; and supply chain integration.
- Value Realisation Management: Formulation of organisational performance targets; establishment of value measurement techniques; definition and monitoring of KPIs; change management strategies; and stakeholder management strategies.

In addition, the scoring of each functional driver from the perspective of each activity system considered the following organisational measures in developing the BAMM appraisal criteria:

- People: Organisational strategy; BIM implementation strategy; collaboration; staffing; training; and business process capability of every activity system.
- Process: BIM standards; organisational BIM objectives; defined roles; effective use of data; supply chain integration; asset lifecycle integration; and value realisation management of every activity system.
- Technology: BIM systems; IT Systems; AM Systems; FM systems; organisational systems architecture; interoperability; data integrity; and data accessibility of every activity system.

The BAMM appraisal criteria is shown in Appendix A.

3.0 BIMAsset Maturity Model (BAMM)

The understanding of organisational maturity is crucial for asset owners to be able to realise BIM business value. Hence, the premise for the development of the BAMM. This is because the more organisations are aware of the maturity of key business processes the greater tendency they have in improving business process capability (Harmon, 2004). The BAMM would enable an owner-operator organisation to determine its strengths and weakness within key BIM-based AM business processes. Furthermore, in order for an organisation to move through the levels of maturity, an organisational culture of continuous improvement should be established. The BAMM consists of five sequential tiers of maturity that demonstrate the development of an organisation in relation to its potential to realise BIM business value (Figure 3). The BAMM appraisal assessment sheet (Figure 2) and criteria (Appendix A) is developed to assess organisational BIM capability in six business activity systems in relation to three functional drivers. The score is aggregated on the assessment sheet and summarised to indicate the maturity level of the organisation.

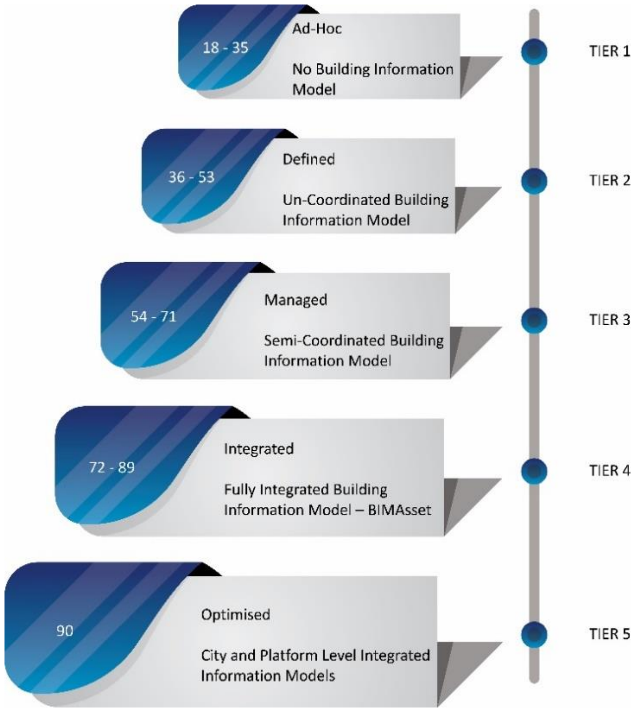


Figure 3: BIMAsset Maturity Model (BAMM)

3.1 Tier 1 – Ad-Hoc

NO BUILDING INFORMATION MODEL

The overall characteristic of this level is that there are ad-hoc BIM-based processes within the organisation. Documentation is in variants of 3D, 2D electronic or paper-based formats with no specific requirements for information models. Also, no COBie information is delivered from the design and construction stages.

3.2 Tier 2 – Defined

UNCOORDINATED BUILDING INFORMATION MODEL

The general organisational trait of this tier is having un-coordinated building information models delivered at the end of design and construction phases. Documentation may lack organisational-level standards for requirements and use within BIM-based AM processes.

3.3 Tier 3 – Managed

SEMI-COORDINATED BUILDING INFORMATION MODEL

The common organisational attribute of this stage is the existence of semi-coordinated building information models. COBie-level information requirements are defined and the delivery process is arbitrary. Here, it is common that the owner-operator organisation lacks a robust strategy for EIR documentation.

3.4 Tier 4 – Integrated

FULLY INTEGRATED BUILDING INFORMATION MODEL – BIMAsset

The main organisational feature of this phase is the existence of fully integrated building information models with access to real-time data at the building or facility level. Here, the organisation is BIM Level 2 compliant in relation to the UK BIM strategy (BSI, 2014). The BIM-based AM system operates with smooth interoperability and AM information is searchable for analysis. Here, the asset owner possesses a robust strategy for EIR documentation. At this stage of maturity, the constantly updated virtual model (BIMAsset) will have an intrinsic value in its own right.

3.5 Tier 5 – Optimised

CITY AND PLATFORM LEVEL INTEGRATED INFORMATION MODELS

The general organisational characteristic of this level is the management of activities at the multi-facility system level, including fully integrated systems combining general access with city level information. Here, the organisation is BIM Level 3 (Digital Build Britain) compliant in relation to the UK BIM strategy (BSI, 2014; HM Government, 2015). The BIM-based AM system operates with smooth interoperability including the availability of asset information at the multi-facility or city level.

4.0 Discussion and Conclusion

The purpose of this paper is to establish the BAMM and demonstrate how it can be used for maturity appraisal for asset owners in relation to BIM business value realisation. The literature review establishes the need for a maturity model that is specific to the domains of BIM, AM and value realisation management. The study reveals that the BAMM can be used to guide organisational appraisal in relation to activity systems and functional drivers. The substantive model enables the asset manager to determine the strength and weakness of business processes and to continuously improve on weaker areas in order to achieve higher maturity and increase the potential of realising BIM business value. This appraisal technique helps serve as a reference point for analysis by an owner-operator organisation when applying value realisation practices in asset operations in order to realise BIM business value. Each maturity level contains focus areas and characteristics of organisational development. The BAMM provides a basis for: (a) assessing various aspects of value realisation management within the organisation; (b) identifying organisational areas where there is room for improvement; (c) demonstrating relationships between all variables and their relationship to BIM business value; and (d) a methodology that is logical and transparent for organisational appraisal in relation to value realisation management of BIM-based processes in AM.

An original contribution of this study is the provision of a maturity model that helps guide asset owners in organisation appraisal in relation to BIM business value. By this, the study answers the research question of how utilise the BAMM for organisational appraisal. Furthermore, as discussed in the literature review, there are a number of maturity models that are applicable to the AEC industry but none is specific to the domains of BIM, AM and value realisation. Thus, a gap in knowledge that the proposed framework in this study fills.

References

Alreshidi, E., Mourshed, M., & Rezgui, Y. (2017). Factors for effective BIM governance. *Journal of Building Engineering*, *10*, 89-101. doi:10.1016/j.jobe.2017.02.006.

Aranda-Mena, G., Crawford, J., Chevez, A., & Froese, T. (2009). Building information modelling demystified: does it make business sense to adopt BIM? *International Journal of Managing Projects in Business, 2*(3), 419 – 434.

Bew, M., & Richards, M. (2008). BIM Maturity Ramp Copyright. *BuildingSmart, CPIC*.

Blommerde, T., & Lynch, P. (2016). A maturity matrix for assessing service innovation capability. *Irish Academy of Management Conference 2016, 31 August - 2 September*. Dublin.

Bosch, A., Volker, L., & Koutamanis, A. (2015). BIM in the operations stage: bottlenecks and implications for owners. *Built Environment Project and Asset Management, 5*(3), 331-343. doi:10.1108/BEPAM-02-2014-0017

BSI. (2014). *Collaborative production of information – Part 4: Fulfilling employer's information exchange requirements using COBie – Code of practice – BS 1192-4:2014.* London: The British Standards Institution 2014; BSI Standards Limited 2014.

Harmon, P. (2004). Evaluating an organisation's business process maturity. *Business Process Trends, 2*(3), 1-11.

HM Government. (2015). Digital built britain: Level 3 building information modelling - strategic plan. Retrieved 07 10, 2019, from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/410096/bis-15-155-digital-built-britain-level-3-strategy.pdf

Kwak, Y. H., & Ibbs, C. W. (2002). Project management process maturity (PM)2 model. *Journal of Management Engineering, 18*(3), 150-155.

Liang, C., Lu, W., Rowlinson, S., & Zhang, X. (2016). Development of a multifunctional BIM maturity model. *Journal of Construction Engineering and Management, 142*(11).

McCuen, T. L. (2008). Building Information Modelling and the interactive capability maturity model. *Associated Schools of Construction*, 1-10.

NIBS. (2007). National Building Information Modeling Standard: Version 1.0.-Part 1: Overview, principles and methodologies. *National building information modeling standard — Washington,DC.*

OGC. (2010). *Portfolio, programme, and project management maturity model (P3M3): Introduction and Guide to P3M3 - Version 2.1.* London: Office of Government Commerce (OGC) - England.

Patrick, R., Munir, M., & Jeffrey, H. (2012). Building Information Modeling (BIM), utilized during the design and construction phase of a project has the potential to create a valuable asset in its own right ('BIMASSET') at Handover that in turn enhances the value of the development. *12th International Conference of Enhanced Building Operations (ICEBO), 23-26 October, 2012.* Manchester, United Kingdom: Proceedings of the International Conference for Enhanced Building Operations (ICEBO) Conference, 23 - 26 October.

Proctor, R. W., & Capaldi, E. (2006). *Why science matters: understanding the methods of psychological research.* Malden, MA: Blackwell Publishing.

Prodan, M., Prodan, A., & Purcarea, A. A. (2015). Three new dimensions to people, process, technology improvement model. In A. Rocha, A. M. Correia, S. Costanzo, & L. P. Reis (Eds.), *New contributions in information systems and technologies advances in intelligent systems and computing, vol 353* (pp. 481-490). London: Springer Link Publishing. doi:10.1007/978-3-319-16486-1_47

Sarshar, M., Haigh, R., Finnemore, M., Aouad, G., Barrett, P., Baldry, D., & Sexton, M. (2000). SPICE: a business process diagnostics tool for construction projects. *Engineering, Construction and Architectural Management, 7*(3), 241-250.

SEI. (1994). *The Capability Maturity Model: guidelines for improving the software process.* Reading, Mass: Carnegie Mellon University Software Engineering Institute, Addison Wesley Longman Inc.

SEI. (2006). *Capability Maturity Model Integration Standard (CMMI) appraisal method for process improvement (SCAMPI) A.* Version 1.2- Method Definition Document: Software Engineering Institute / Carnegie Melon.

Succar, B. (2010). Building Information Modelling maturity matrix. In J. Underwood, & U. Isikdag, *Handbook of research on Building Information Modelling and construction informatics: concepts and technologies* (pp. 65-103). Hershey, PA: IGI Publishing. doi:10.4018/978-1-60566-928-1.ch004

Succar, B., Sher, W., & Aranda-Mena, G. (2007). A proposed framework to investigate Building Information Modelling through knowledge elicitation and visual models. *Proceedings of the Australasian Universities Building Education Association (AUBEA 2007), 4-5 July*. Melbourne, Australia.

Vaidyanathan, K., & Howell, G. (2007). Construction Supply Chain Maturity Model - Conceptual Framework. *In:, Pasquire, C.L, C.L. & Tzortzopoulos, P., 15th Annual Conference of the International Group for Lean Construction*, (pp. 170-180). East Lansing, Michigan, USA.

Wijekoon, K. A., Manewa, A., Ross, A., & Marsh, D. (2016). Towards Facilities Information Management Through BIM. Colombo, Sri Lanka: The 5th World Construction Symposium 2016: Greening Environment, Eco Innovations and Entrepreneurship 29-31 July 2016.

Yin, R. K. (2003). *Case Study Research: Design and Methods* (3rd ed.). Thousan Oaks: Sage Publications Inc.

Semantic interoperability between BIM and GIS – review of existing standards and depiction of a novel approach

Ana ROXIN[1*], Elio HBEICH[2]
[1] Univ. Bourgogne Franche-Comté (UBFC) – LIB EA7534
[2] Information System and Applications Division, CSTB, Sophia Antipolis 06560, France
* email: ana-maria.roxin@ubfc.fr

Abstract

When it comes to Big Data ecosystems, main technical challenges pertain to defining links between data, information and knowledge, thus reaching interoperability. Interoperability issues are addressed in the context of data curation related tasks. Interoperability is a major pre-requisite for achieving data automation, validation, thus fighting counter-productiveness (notably through data incentivisation). The demand for interoperable, reusable and open data is more and more present, thus pushing forward the research for innovation data curation approaches. This article gives a high-level description of our approach for bridging the interoperability gap among GIS (Geographic Information Systems) and BIM (Building Information Modelling) systems. After a summary of standards existing in the considered application domains, we further specify the interoperability issues applying and present existing approaches for reaching interoperability among models. Based on the study of these approaches, we then discuss our approach and the related multi-scale modelling. We illustrate how it allows reaching federation among GIS and BIM systems, while supporting consistent reasoning on the features of the federated systems. We conclude with a listing of future work to be done in order to reach this vision.

Keywords: BIM, GIS, Semantic Interoperability, Cyber-Physical Systems, Granularity

1. Introduction

Today's urban scopes come with overwhelming challenges that concern multiple stakeholders or territorial communities. Thus, we are witnessing more collective practices along with innovative rules and norms aiming to conceive multi-level, multi-scale solutions addressing those challenges associated with the vision of smart cities. More specifically, when considering knowledge automation, smart cities become sandboxes for problem-solving, where numerous dimension such as spatial economic, social, aspects should be taken into consideration to provide answers to local challenges: climate change, energy efficiency, etc. Complexity is pushed at an even higher level when taking into consideration the different standards and regulations that apply on each of the aspects listed above. Notably, regarding spatial aspects there are two main standard families that apply: a) Standards pertaining to Building Information Modelling (BIM), promoted by buildingSmart International (bSI) and the ISO TC 59 b) Standards pertaining to Geographic Information Systems (GIS), promoted by the Open Geospatial Consortium (OGC) and ISO TC 211. While GISs allow integrating of geographic information, BIM aims to management building information throughout its lifecycle (e.g. from design to demolition). While both standard families come with structured information models and processes for describing aspects from the considered domains, no links have been defined between the two worlds. Thus when it comes to implementing knowledge automation approaches in the context of smart cities, data must be seamlessly integrated into a system ensuring its consistent interpretation by the machine. For addressing this issue, we present our approach for interoperability, based on federation meta-model. The article is divided as follows: section 2 introduces BIM and GIS information models as defined in the respective standard families, section 3 ,4 introduce related work and a review of existing standard approaches for interoperability, while section 5 describes BIM and GIS barriers. Our approach is discussed in section 6 and finally we conclude in section 7.

2. The need for interoperability

2.1 BIM information model

Building Information Modelling (BIM) is a 3D model-based process that gives architecture, engineering, and construction professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure. BIM model can be used for analysis to explore design options and to create visualizations that help stakeholders understand what the building will look like from start to finish. Finally, BIM describes a method of work by which all relevant information for the life cycle of the building is integrated, administered and exchanged among the project participants. ISO 29481 (*ISO 29481-1: Building information models - Information delivery manual - Part 1: Methodology and format*, 2016, p. 294) defines BIM as a shared digital representation of an object built to facilitate design, construction and operating process and form a reliable basis for decision-making. The first stage of BIM standardization was carried out in 1999 by IAI (now buildingSmart International) (Wang, 2012) . BIM relies on the following international standards:

- Information Delivery Manual (IDM) specifies how information is exchanged in a process. It is based on the ISO 29481 standard and is defined as an interchange agreement. IDM is a natural language description of the exchange.
- Model View Definition[1] (MVD) describes the data model needed to meet the exchange requirements described in the IDM. The underlying methodology is described by Part 3 of ISO 29481 (ISO 29481-3: Building information models - Information delivery manual - Part 3: Model View Definition., 2010, p. 294).
- Industry Foundation Classes (IFC) (Liebich et al., 2013) represent the conceptual model for buildings and comprises all classes and relations for representing a building (ISO 16739: industry Foundation (IFC) for data sharing in the construction and facilities management, 2013, p. 167) The IFC model is specified in EXPRESS and complies with ISO 10303 (ISO 10303: Industrial automation systems and integration -- Product data representation and exchange -- Part 21: Implementation methods: Clear text encoding of the exchange structure, 2016) also called STEP part 21 (Standard for the Exchange of Product model data). STEP focuses on the representation and exchange of product data and aims to integrate the processes of design, development, manufacture, and maintenance (see figure 1).

2.2 The GIS standard family

GIS allows capturing, storing, handling and analysing geographical data (Sahoo, 2017). The main international organization developing standards for geospatial information is ISO TC 211. It specifies methods, tools, and services for data management, acquisition, processing, accessing, presenting, and transferring such data digitally (*ISO 191xx series of geographic information standards- Concepts and organization of the reference model defined in ISO standard 19101*, 2005). The approach to conceptual modelling in the ISO 19100 series is based on the principles described in the ISO CSMF (Conceptual Schema Modelling Facilities). This conceptual schema includes four levels: metamodel, conceptual (abstract) schemas, conceptual (applications) schemas and implementation schemas (see figure 2). The first level contains the General Feature Model defined in ISO 19109, which specifies the concepts, terminology, operations, and assumptions needed to build the basic constructs in the Conceptual Schema layer level. The contents of the meta-meta model level is usually expressed in natural language and is not itself subject to standardization. Conceptual Schema layer contains the definitions of the concepts, terminology, operations and assumptions needed to construct application schemas.

[1] http://www.buildingsmart-tech.org/specifications/mvd-overview

Application schemas define the types of features and processes that are instantiated to produce datasets of geographic information. Application schemas are expressed using syntax and semantics from one or more conceptual schemas. The “bottom” layer contains the actual data that is defined by the application schema at the application model level.

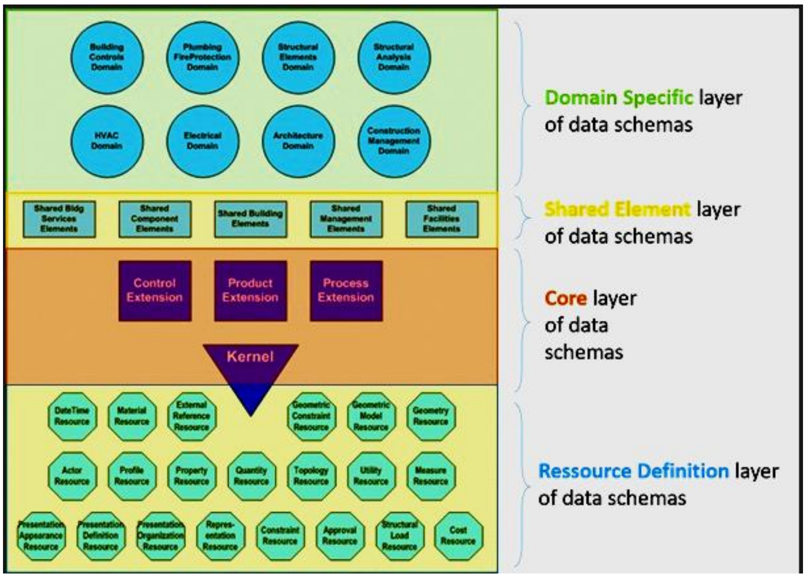


Figure 1: IFC layers of data schemas (ISO 16739-1) and modelled in the EXPRESS Schema (ISO 10303-11).

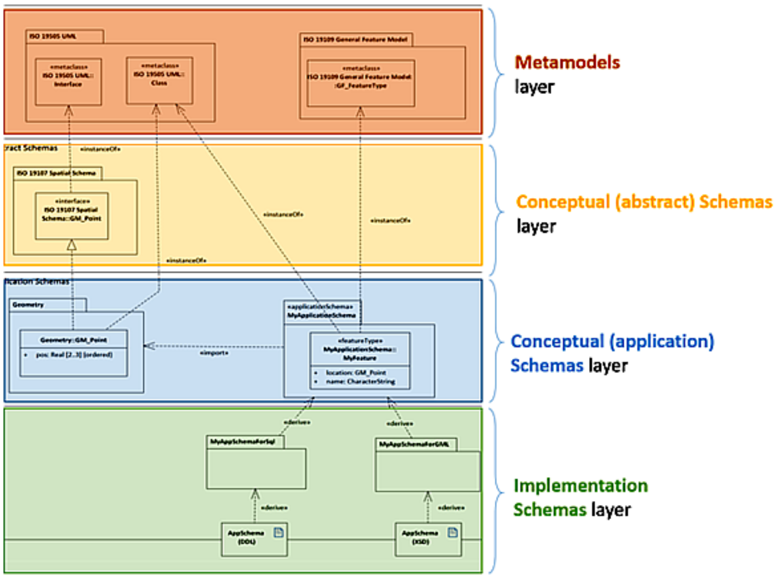


Figure 2: ISO TC 211 Conceptual model (ISO 191xx series 2006)

3. Related Work

In this section we are presenting previous work done to achieve BIM and GIS interoperability: (Deng, Cheng, & Anumba, 2016) presents a framework that can achieve automatic data mapping between IFC and CityGML in different level of details (LOD), using a reference ontology. However, the study only achieved bidirectional mapping for the building models. (Mignard & Nicolle, 2014) introduces a semantic extension called Urban Information Modelling (UIM), that defines spatial, temporal and multi-representation concepts using extensible ontology. However, the main drawback of this approach persist in the usage of database to store the instances of the ontology. (Hor, Sohn, Claudio, Jadidi, & Afnan, 2018) solves the interoperability between BIM and GIS by applying the following steps: 1) transforming IFC to RDF, 2) transform GIS to RDF, and finally 3) using the GMO algorithm to map between the Ontologies. However, the algorithm needs more enhancement as it does not take into count all semantic information. (Floros, Pispidikis, & Dimopoulou, 2017) presents a methodology to transform the IFC model into CityGML as a potential way to achieve interoperability between GIS and BIM. However, the methodology presented did not investigate a fully complex model, and many semantic information was lost in the process. Our study and research focus on connecting BIM and GIS domains while keeping them independent from each other (federation approach) which is different from the previous approaches presented. In the next section we are going to present the challenges and approaches we are going to adapt to solve interoperability between the two domains.

4. The need for interoperability

4.1 The concept of interoperability and its flavours

Several definitions exist for interoperability concept: the ISO alone holds more than a dozen standards, each coming with its own definition of "interoperability". Interoperability is defined as the "capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units". This definition implies that interoperable systems can either exchange information or be accessed with a single method. In order to further specify and tackle the interoperability issues among BIM and GIS, we follow the General System Theory (GST) abstraction (Von Bertalanffy, 1969) and adapt it to the previous definition of CSPs. We thus consider BIM and GIS abstracted as systems comprising several parts, each part exhibiting some behaviour (that can be different from the overall system's behaviour). These behaviours and their related components, mechanisms and processes are monitored, managed and coordinated by some computer. Hence interoperability is achieved using standards that enable behaviours of parts of the system and the overall behaviour of the system to cooperate seamlessly in order to reach a common goal or function. With these definitions and statements in mind, the next sections present existing levels of interoperability and discuss existing standard approaches for implementing interoperability.

4.2 Levels of interoperability

Existing standards identify three main levels of interoperability, namely: data, syntactic, and semantic interoperability. These layers are connected and build upon each other, lower levels providing elements required by upper levels functionalities (Kubicek, Cimander, & Scholl, 2011). Figure 3 illustrates those levels along with their definitions as pertaining to ISO standards. Sometimes referred at as physical interoperability, the issues pertaining to the data level of interoperability have been long resolved with the adoption of hardware standards such as Ethernet (Hollenbeck, n.d.); along with standard protocols for lower layers of the ISO network architecture e.g. TCP/IP ((Postel, 1981a) (Postel, 1981b)) and HTTP ("Hypertext Transfer Protocol -- HTTP/1.1," n.d.). Syntactic interoperability addresses the syntax of messages exchanged among CSPs considered artefacts. The related issues have been resolves through the adoption of XML and related syntax standards e.g. HTML, WSDL ("Web Service Definition Language (WSDL)," 2011) and SOAP ("SOAP Specifications," n.d.). Semantic interoperability addresses the meaning of the messages exchanged and related issues have not yet been resolved by existing standards and approaches. Semantic Web standards and languages allow specifying such meaning, by means of formal and explicit specifications of conceptualisations e.g. ontologies. Considering the different Semantic Web languages existing, semantic interoperability comes with different flavours:

- Minimum semantic interoperability is enabled by the use of RDF ("RDF - Semantic Web Standards," n.d.) and allows specifying the minimum knowledge than can be exchanged through a sentence e.g. what is expressed through the sentence itself. Such low level of semantic interoperability requires further manual and/or automated handling of the exchanged data.

- *Extended* semantic interoperability allows defining a minimal ensemble of beliefs onto which two computer agents agree. Such ensemble of beliefs allows computer agents to make new deductions from the implicit facts contained in the message they exchange. Such level of semantic interoperability is enabled by the use of RDF Schema ("RDF Schema 1.1", n.d).
- *Full* semantic interoperability is enabled by the usage of the OWL ontology language family. An OWL shared ontology can specify what computer agents may agree upon, while preventing them from making erroneous deductions. It allows specifying a knowledge conceptualization bounded to a given domain.

Following these definitions, semantic interoperability denotes the ability of applications and business partners to interpret exchanged data in a consistent way, implying explicit and formal structures. Even though, ontologies are explicit specifications of shared conceptualisations of a knowledge (Studer, Benjamins, & Fensel, 1998), relying on it doesn't lower semantic heterogeneity of the so conceived knowledge models. Even if, these ontologies have been defined, they are independently from one another, with no semantic links formed to identify and align concepts and relations between those ontologies. Thus, no consistent interpretation can be delivered based on those ontologies solely. The need for defining links among existing knowledge models pertaining to BIM and GIS becomes urgent. And for doing so, the same approaches used for coupling models can be applied to ontologies. In this context, the ISO standard about the integration of industrial automation systems (*ISO 14258: Industrial Automation Systems- concepts and rules for enterprise models*, 1998) defines three possibilities: models can be *integrated*, *unified* or *federated*. These three types of approaches were more recently considered as standard interoperability approaches in the context of ISO 11354, defining the Enterprise Interoperability Framework or EIF (*ISO 11354-1: Advance automation technologies and their applications – Requirements for establishing manufacturing enterprise process*, 2011). The sections below further discuss these three approaches, notably based on their specification in the EIF.

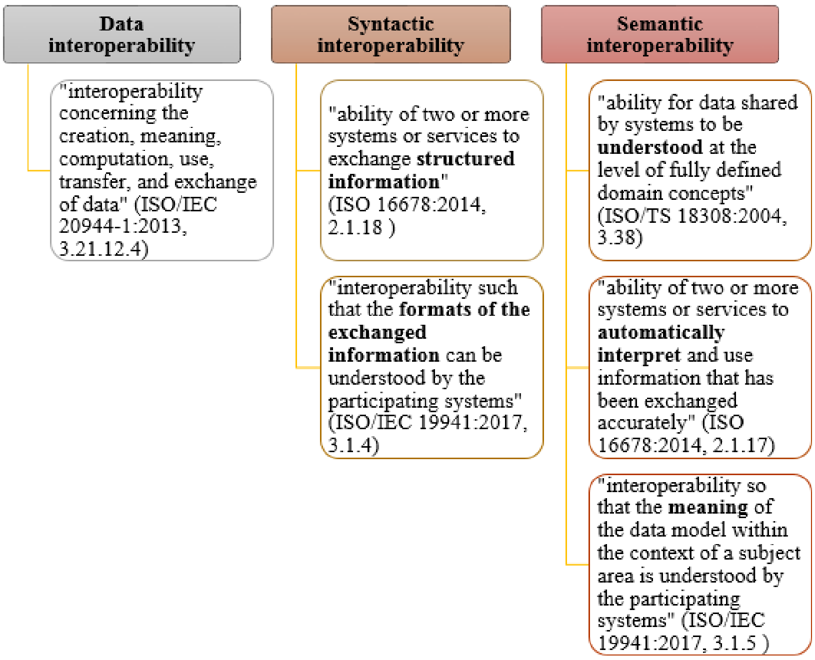


Figure 3: Levels of interoperability

4.3 Standard Approaches for Semantic Interoperability

In the context of an ***integrated approach***, all exchanged elements have to be represented with respect to a common form. Such common form must have an associated level of expressiveness allowing to capture the specific details of the elements exchanged, especially those impacting interoperability. All elements and artefacts in the considered system or organization have to be described according to the common form, even if the latter isn't built upon an existing International standard. This approach is suitable when designing and implementing new systems rather than when reengineering existing systems for interoperability (Métral, Billen, Cutting-Decelle, & van Ruymbeke, 2010t). An example of ISO standards implementing model integration are the "Industrial automation systems and integration — Product data representation and exchange" (*ISO 10303: Industrial automation systems and integration -- Product data representation and exchange -- Part 21: Implementation methods: Clear text encoding of the exchange structure*, 2016). ***Unified approaches*** require a common meta-model. In its simplest version, such meta-model can be a reference vocabulary, while in a more advanced version it can represent a complete ontology. Defined as a meta-model, it allows establishing semantic equivalences among considered concepts or entities. All other considered models with their related syntaxes and semantics have to be mapped to the common meta-model. Using the common meta-model, a translation between the constituent models is possible even though they might encounter loss of some semantics or information (*ISO 11354-1: Advance automation technologies and their applications – Requirements for establishing manufacturing enterprise process*, 2011). Example of ISO standards implementing unified model are TC184 "Industrial data" (SC4) and "Interoperability, integration and architectures for enterprise systems and automation applications" (SC5) sub-committees. ***Federated approaches*** implies that no partner imposes their models, languages, or methods of work. Such approaches do not imply a common form or a common meta-model (*ISO 11354-1: Advance automation technologies and their applications – Requirements for establishing manufacturing enterprise process*, 2011). They mainly apply to contexts where the entities considered for interoperability rely on too different or too complex vocabularies or methodologies. In a federated approach, each entity needs to adapt its processes and methods. For reaching interoperability in such a context, mappings must be specified among input and output information of the considered entities or artefacts. Remaining inconsistencies must be manually addressed. Implementing successful federation among organizations or systems comes with more challenges than the two previous approaches. As an example of such implementation, we may cite the federation approach in ISO 16100 "Manufacturing Software Interoperability Services" (ISO 16100: Industrial automation systems and integration -- Manufacturing software capability profiling for interoperability, 2011, p. 161).

5. Bringing semantic interoperability between BIM and GIS

While BIM comes with detailed 3D visualization and various functionalities to organize and manage huge volumes of data related to buildings, GIS environments are highly customizable, well-equipped for multi-dimensional analysis, and ideal for projects involving multi-site environments. Even though one is usually struck by the differences among the methods and processes, there is a general tendency of combining them in order to benefit from their cumulated advantages. As both domains are complimentary to each other, reaching interoperability would bring highly productive outcomes in the field of digital AECO (Architecture, Engineering, Construction and Operations). However, reaching such vision comes with several challenges, the main ones being listed below:

1. Coordinate systems and spatial referencing: GIS use two-dimensional real-world coordinates (RWC 9), while BIM systems use three dimensional relative coordinates between objects, with a reference to RWC at root object. GIS is based on a global spatial reference system and use boundary representation. BIM applications use local spatial reference systems.
2. Temporal aspects: In BIM applications, a building object is characterized by its geometrical representations and its geometrical and non-geometrical properties. Such object can have several geometrical representations, as they each correspond to a different point of view. Still, the BIM standards do not define any links between these geometrical representations and geometrical properties of the considered building object. Initially such permissiveness was wanted for BIM applications (in order to cope with how levels of detail are handled in GIS systems). But today, standards should restrict or specify explicitly the possible choices. The level of permissiveness allowed by today's standards hinders the efficient implementation of BIM ecosystems, as it all depends of the choices made at the level of software implementations

3. Semantics: BIM and GIS use different vocabularies to describe their entities and properties. No equivalencies have been defined among these elements. While bSI and there is no define link between the IFC and GIS vocabulary has developed the bSDD (buildingSmart Data Dictionnary) listing all existing terms and properties in the IFC standard, there are no explicit links defined between the bSDD vocabulary and other similar initiatives such as the French standard XP P07-150 (AFNOR PPBIM), promoted in the context of CEN/TC 442 WG4. Such semantic links are essential for implementing consistent information exchanges based on the IFC format.

6. Achieving BIM/GIS semantic interoperability

Considering the above approaches, along with our application context e.g. knowledge automation in smart cities, approaches based on federation appear as the most suitable. Indeed, integrated approaches imply using one single common model according to which all other models are conceived and interpreted. As mentioned above, these approaches are best suited when engineering novel CPSs, and fail in addressing all subtleties of existing CPSs. More specifically, in the context of our approach, two axes are considered for federation - horizontal, and vertical. For the first case, we consider relying on an existing approach namely the federated architecture for OWL ontologies or FOWLA (de Farias, Roxin, & Nicolle, 2015). For the latter, Hobbs' granular partition theory (Hobbs, 1985) gives several interesting perspectives and future work directions. Both approaches are discussed in the sections below. Following the database federation approach (Sheth & Larson, 1990), FOWLA is an approach relying on SWRL rules for federating autonomous ontologies (including TBox and ABox). The architecture contains two main components: The Federal Descriptor and the Federal Controller (de Farias, Roxin, & Nicolle, 2015). The first is responsible of identifying missing concept instantiations and identifying new alignments (based on previously defined ones). The latter is mainly responsible of executing SPARQL queries. More specifically, it comes with a Rule Selector module that is responsible of selecting only the subset of SWRL rules that allow returning results pertaining to the considered SPARQL query. Granularity is the extent to which a system is composed of distinguishable pieces or grains. It can either refer to the extent to which a larger entity is subdivided, or the extent to which groups of smaller indistinguishable entities have joined together to become larger distinguishable entities. For example, a kilometre broken into centimetres has finer granularity than a kilometre broken into meters. Information granules, as the name itself stipulates, are collections of entities, usually originating at the numeric level, that are arranged together due to their similarity, functional adjacency, indistinguishability, coherency or alike (Pedrycz and Bargiela, 2002). In order to best understand how this can be applied to our context, let us take an example. Consider planning a trip. In this case, the route one has to travel can be abstracted as a one-dimensional curve. When considering an infrastructure use case involving for example works on the asphalt on the road, one can no longer approximate the road as a curve, but has to take into account its volume – it thus becomes a 3D volume. With the indiscernibility relation previously defined, one can identify predicates pertaining to the use cases considered. In the first one, two points in the asphalt, identified through their respective coordinates will be undiscernible. An example of a predicate pertaining in the context of this first use case would be the distance between one point on the road and the destination point. Granular computing is an approach orthogonal to existing modelling approaches. It allows separating one knowledge domain into smaller pieces of knowledge, by means of consistent and structured methods, thus building a granular perspective. This allows consistent reasoning on these smaller pieces of knowledge but also on the whole knowledge domain. Still, while several formal models of granularity have been defined in literature (Mani, 1998), (Keet, 2008), the different granular perspectives have to be explicitly and formally defined, with regard to the considered application domain. Moreover, in applications involving context awareness, one has to further study and specify the relation between knowledge granularity and context granularity. Given the above considerations, a first step in our approach addresses consistent semantic modelling of BIM and GIS information. Together with experts from the domain of BIM and GIS, the next steps of our work will investigate what alignments can be defined among BIM/GIS concepts and models (as defined in the respective ISO TC 211 and IFC ontologies). As such, the rules defined in the (ISO 191xx standard family for application schemas (*ISO 19109: Geographic information- rules for application schema*, 2015, p. 109) and feature catalogues (*ISO 19110: Geographic information -- Methodology for feature cataloguing*, 2016) allow to represent IFC by means of UML. But as UML is not formal, additional alignments have to be investigated. More specifically, our future work will consider the following levels of alignments:

- Alignments among metamodels: General Feature Model (GFM) of ISO 19109 has to be compared with the IFC elements contained in the core layer of data schemas of the IFC schema. IFC classes such as IfcKernel, IfcControlExtension, IfcProcessExtension, IfcProductExtension have to be mapped to their equivalents in ISO 19109 GFM.
- Alignments among abstract conceptual GIS schemas and data schemas contained in the Resource Definition layer of IFC: Several geometry and topology elements from the GIS temporal schema (ISO 19107: Geographic information -- Spatial schema, 2003) are equivalent to sub-classes of IfcDateTimeResource or IfcTopologyResource. Also several elements from ISO 19107 Temporal schema have equivalents in the IFC terminology notably subclasses of IfcGeometryResource and IfcPresentationAppearanceResource. IFC classes such as IfcGeometricConstraintResource or IfcGeometricModelResource have to be mapped to their equivalent concepts in spatial referencing (ISO 19111: Geographic information -- Referencing by coordinates, 2019).
- Alignments among application schemas in GIS and domain specific and shared elements IFC data schemas: IFC classes such as IfcKernel, IfcControlExtension, IfcProcessExtension, or IfcProductExtension have to be mapped to their equivalent concepts in ISO 19109 GFM. Concepts from the IFC Shared Elements layer of data schemas have to be mapped to their respective equivalents in ISO 19130 (ISO/TS 19130: Geographic information - Imagery sensor models for geo-positioning, 2010).

With the above considerations in mind, future work to be done in the context of this approach also involves the following items:

- Missing ontologies: for example, which ontology mediation will be used to establish compatibility on terminological level
- Missing links: some can be identified fairly easily, others require exchanges with business experts and are more complex to define.
- Granular approaches impact: the concept of granularity, seems intuitive and easy to implement, however the manner of ontologies, the associated levels and perspectives must be explicitly and formally specified by integrating the characteristics of the domain of knowledge concerned (Livi & Sadeghian, 2016)
- In addition, when it comes to integrate granularity into application that handle business knowledge it is necessary to investigate, define and specify the granularity if knowledge and it is context.

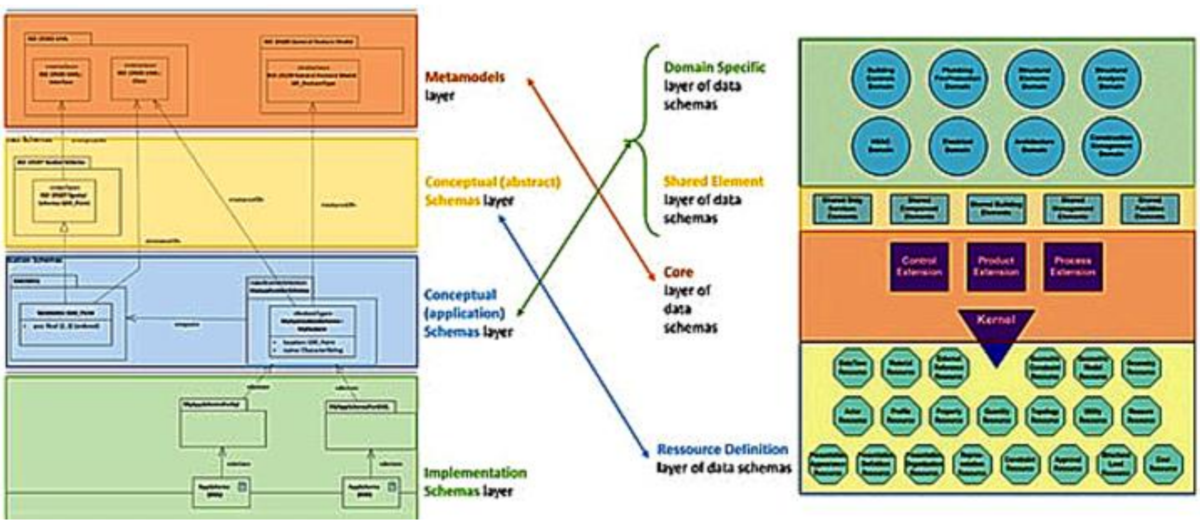


Figure 4: Links among the layers of the information models considered

7. Conclusion

Previous studies aim to integrate BIM to GIS or vis versa. However, our object aims to remove the barrier that exists between the two domains based on their standards and keep them independent from each other. In this article we aim at defining the interoperability issue among GIS and BIM systems, and specifying an approach addressing this issue. Our approach relies on Semantic Web technologies and granular approaches for performing two-axis federation. In our approach, we do not seek to merge BIM and GIS, neither to promote one over the other, hence we intend to reuse the FOWLA approach and its advantages in terms on lightly-coupled ontology federation. Granular approaches further help in conceiving and managing different abstractions of the same context or scape, which is highly pertaining to the urban environments considered by our application domain. The purpose of achieving interoperability between BIM and GIS is to specify and implement means to describe buildings along with their environment, at different scales.

References

Beetz, J., van Leeuwen, J., & de Vries, B. (2009). IfcOWL: A case of transforming EXPRESS schemas into ontologies. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 23(1).

Charalabidis, Y., Lampathaki, F., & Askounis, D. (n.d.). A Review of Interoperability Standards And Initiatives In Electronic Government. 16.

Chen, D., Doumeingts, G., & Vernadat, F. (2008). Architectures for enterprise integration and interoperability: Past, present and future. Computers in Industry, 59(7), 647–659.

Deng, Y., Cheng, J. C. P., & Anumba, C. (2016). Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison. Automation in Construction, 67, 1–21.

Dassisti, M., Jardim-Goncalves, R., Molina, A., Noran, O., Panetto, H., & Zdravković, M. M. (2013). Sustainability and Interoperability: Two Facets of the Same Gold Medal. In Y. T. Demey & H. Panetto (Eds.), On the Move to Meaningful Internet Systems: OTM 2013 Workshops (Vol. 8186, pp. 250–261).

Farias, T. M., Roxin, A., & Nicolle, C. (2015). FOWLA, A Federated Architecture for Ontologies. In N. Bassiliades, G. Gottlob, F. Sadri, A. Paschke, & D. Roman (Eds.), Rule Technologies: Foundations, Tools, and Applications (Vol. 9202, pp. 97–111). https://doi.org/10.1007/978-3-319-21542-6_7

Floros, G., Pispidikis, I., & Dimopoulou, E. (2017). INVESTIGATING INTEGRATION CAPABILITIES BETWEEN IFC AND CITYGML LOD3 FOR 3D CITY MODELLING. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-4/W7, 1–6. https://doi.org/10.5194/isprs-archives-XLII-4-W7-1-2017

Gao, G., Liu, Y.-S., Wang, M., Gu, M., & Yong, J.-H. (2015). A query expansion method for retrieving online BIM resources based on Industry Foundation Classes. Automation in Construction, 56, 14–25. Hobbs, J. (1985). granularity.pdf.

Hollenbeck, R. (n.d.). The IEEE 802.3 Standard (Ethernet): 24.

Hypertext Transfer Protocol -- HTTP/1.1. (n.d.). Retrieved May 27, 2019, from https://www.ietf.org/rfc/rfc2616.txt

IEEE Standard Glossary of Software Engineering Terminology, (1990). The Institute of Electrical and

Electronics Engineers 345 East 47th Street, New York, NY 10017, USA,

ISO 191xx series of geographic information standards- Concepts and organisation of the reference model defined in ISO standard 19101. (2005, October 11).

ISO 10303: Industrial automation systems and integration -- Product data representation and exchange -- Part 21: Implementation methods: Clear text encoding of the exchange structure. (2016). Retrieved from http://ComputingEngineering.asmedigitalcollection.asme.org/article.aspx?articleid=1399190

ISO 11354-1: Advance automation technologies and their applications – Requirements for establishing manufacturing enterprise process. (2011).

ISO 14258: Industrial Automation Systems- concepts and rules for enterprise models. (1998).

ISO 15704: Industrial automation systems -- Requirements for enterprise-reference architectures and methodologies. (2000).

ISO 15745-3 Industrial automation systems and integration -- Open systems application integration framework -- Part 3: Reference description for IEC 61158-based control systems. (2003).

ISO 16100: Industrial automation systems and integration -- Manufacturing software capability profiling for interoperability. (2011).

ISO 16678: Guidelines for interoperable object identification and related authentication systems to deter counterfeiting and illicit trade. (2014).

ISO 16739: industry Foundation (IFC) for data sharing in the construction and facilities management. (2013).

ISO 19107: Geographic information -- Spatial schema. (2003).

ISO 19109: Geographic information- rules for application schema. (2015).

ISO 19110: Geographic information -- Methodology for feature cataloguing. (2016).

ISO 19111: Geographic information -- Referencing by coordinates. (2019).

ISO 29481-1: Building information models - Information delivery manual - Part 1: Methodology and format. (2016).

ISO 29481-3: Building information models - Information delivery manual - Part 3: Model View Definition. (2010).

ISO/IEC/IEEE 24765: Systems and software engineering – Vocabulary. (2017).

ISO/TS 19130: Geographic information - Imagery sensor models for geo-positioning. (2010).

Keet, C. M. (2008). A Formal Theory of Granularity. 268.

Kubicek, H., Cimander, R., & Scholl, H. J. (2011). Layers of Interoperability. In H. Kubicek, R. Cimander, & H. J. Scholl, Organizational Interoperability in E-Government (pp. 85–96).

Liebich, T., Chipman, T., & Weise, M. (n.d.). Specification of a standardized format to define and exchange Model View Definitions with Exchange Requirements and Validation Rules.

Livi, L., & Sadeghian, A. (2016). Granular computing, computational intelligence, and the analysis of non-geometric input spaces. Granular Computing, 1(1), 13–20.

Mach, M. A., & Owoc, M. L. (2010). Knowledge Granularity and Representation of Knowledge: Towards Knowledge Grid. In Z. Shi, S. Vadera, A. Aamodt, & D. Leake (Eds.), Intelligent

Information Processing V (Vol. 340, pp. 251–258). https://doi.org/10.1007/978-3-642-16327-2_31

Mani, I. (1998). A Theory of Granularity and its Application to Problems of Polysemy and Underspeci cation of Meaning. 11.

Mashinchi, M. R., & Selamat, A. (n.d.). Granular Computing and Inexactness. 4.

Mignard, C., & Nicolle, C. (2014). Merging BIM and GIS using ontologies application to urban facility management in ACTIVe3D. Computers in Industry, 65(9), 1276–1290. https://doi.org/10.1016/j.compind.2014.07.008

Pedrycz, W., & Bargiela, A. (2002). Granular clustering: a granular signature of data. IEEE Transactions on Systems, Man and Cybernetics, Part B (Cybernetics), 32(2), 212–224.

Postel, J. (1981a). Internet Protocol. Retrieved May 27, 2019, from https://tools.ietf.org/html/rfc791

Postel, J. (1981b). Transmission Control Protocol. Retrieved May 27, 2019, from https://tools.ietf.org/html/rfc793

RDF - Semantic Web Standards. (n.d.). Retrieved May 13, 2019, from https://www.w3.org/RDF/

RDF Schema 1.1. (n.d.). Retrieved May 13, 2019, from https://www.w3.org/TR/rdf-schema/

Sahoo, P. M. (2017). Introduction to Geographic Information System. 10.

Sheth, A. P., & Larson, J. A. (1990). Federated Database Systems for Managing Distributed, Heterogeneous, and Autonomous Databases'. ACM Computing Surveys, 22(3), 55.

SOAP Specifications. (n.d.). Retrieved May 13, 2019, from https://www.w3.org/TR/soap/

Studer, R., Benjamins, V. R., & Fensel, D. (1998). Knowledge engineering: Principles and methods. Data & Knowledge Engineering, 25(1–2), 161–197. https://doi.org/10.1016/S0169-023X(97)00056-6

Vernadat, F. B. (2002). Enterprise modeling and integration (EMI): Current status and research perspectives. Annual Reviews in Control, 26(1), 15–25. https://doi.org/10.1016/S1367-5788(02)80006

Volk, R., Stengel, J., & Schultmann, F. (2014). Corrigendum to "Building Information Modeling (BIM) for existing buildings — Literature review and future needs" [Autom. Constr. 38 (March 2014) 109–127]. Automation in Construction, 43, 204. https://doi.org/10.1016/j.autcon.2014.02.010

Von Bertalanffy, L. (1969). The History and Status of General Systems Theory. Academy of Management Journal, 15(4), 407–426. https://doi.org/10.2307/255139

Wang, X. (2012). BIM Handbook: A guide to Building Information Modeling for owners, managers, designers, engineers and contractors. Construction Economics and Building, 12(3), 101–102.

Web Service Definition Language (WSDL). (2011). Retrieved May 13, 2019, from https://www.w3.org/TR/2001/NOTE-wsdl-20010315

Zhang, L., & Issa, R. R. A. (n.d.). Development of IFC-based Construction Industry Ontology for Information Retrieval from IFC Models. 9.

Micro BIM adoption: Identifying the Profiling Patterns of adoption using a Systems Thinking Approach

Ahmed Louay Ahmed[1*] and Mohamad Kassem[2]
[1]Lecturer, Department. of Architecture, University of Technology, Baghdad, Iraq.
[1]PhD Researcher, Sheffield School of Architecture, University of Sheffield, Sheffield, UK.
[2]Department of Mechanical and Construction Engineering, Northumbria University Newcastle, United Kingdom.
*email: 90006@uotechnology.edu.iq ; alaahmed1@sheffield.ac.uk

Abstract

Understanding the dynamics of Building Information Modelling (BIM) adoption in organisations – referred to in the remainder of the paper as 'micro BIM adoption' – is key to develop and implement successful BIM implementation strategies. In particular, understanding the causal chains between multiple factors driving organisations towards the decision to adopt BIM is still an area that requires further investigation. This paper investigates micro BIM adoption by considering both the multi-staged nature of BIM adoption and the interactions between such stages and an extensive array of adoption factors. By doing so, the paper is recognising the micro BIM adoption system as a complex system which can be investigated using a Systems Thinking model approach. Causal Loop Diagrams (CLD) were used to profile the adoption patterns within the UK Architecture sector. Six key feedback loops describing the key profiling patterns of micro BIM adoption are identified and described in this paper.

The identified patterns can be used to support the establishment of micro BIM adoption strategies. For example, the identified patterns can inform the development of tailored initiatives and actions that exert effect on the key nodes (i.e., adoption factors) affecting the BIM adoption system and can be used to prioritise effort (e.g., investment) in such actions.

Keywords: BIM, Adoption, Diffusion, System Thinking model, Causal Loop Diagrams (CLD).

1. Introduction

In recent years digital transformation and innovation have significantly permeated every topic within the construction sector, in both industrial and academic discourse. BIM connotation has been always on the rise since its inception; from its earliest definitions focussed on technologies and tools, BIM is now considered as the "current expression of digital innovation within the construction sector" (Succar and Kassem, 2015, p.64). This study justified the need for new studies on BIM adoption studies. This need is founded on a clear research gap, represented by the lack of studies that consider simultaneously (1) the multifaceted nature of BIM, (2) the multi-staged nature of the BIM adoption process, and (3) an extensive array of drivers affecting the BIM adoption process. This paper will address these limitations and develops Causal Loop Diagrams (CLD) for the BIM adoption process. Following the literature review that identifies the gap, the paper describes the CLD and discussed their implications.

2. Literature review and gap

Some of the key characteristics of existing studies on BIM adoption include: a focus on BIM diffusion - after BIM has been adopted – and on developing approaches for forecasting BIM diffusion (Gholizadeh et al., 2018). For instance, studies have used ‘Bass Model’ to predict the rate of BIM technologies diffusion within a certain period (i.e., 2012 – 2022) within the Chinese construction industry (Tang and Yi, 2015). There are also some shortcomings in existing BIM adoption studies include the use of key terms and concepts (e.g., implementation, readiness, adoption, diffusion) interchangeably or without a clear expression of the demarcation stance adopted for the terms. For example, (Al-Shammari, 2014), (Haron et al., 2014), and (Attarzadeh et al., 2015) have all interchangeably used the terms ‘Adoption’ and ‘Implementation’. This blurs the distinction between interrelated concepts such as adoption, implementation, and diffusion (Ahmed and Kassem, 2018). In addition, lack of information about the position of studies in relation to the innovation adoption stages (i.e., Awareness stage, Intention stage, and Decision stage) which are proposed by Rogers (2003) in his innovation decision process. Moreover, the limited investigations of interplays between adoption factors and specific instances of some factors such as organisation size (i.e., micro, small, medium, and large) (Hosseini et al., 2016) and external isomorphic factors (e.g., market-wide BIM mandate by a government or a public agency) and how such interplays vary over time. Also, lack of investigative effort covering a whole sector (e.g., Architecture sector) within a defined market (e.g., the United Kingdom). Finally, the dispersion in investigating the BIM adoption drivers and factors – across several studies – as a result of the specific theoretical lenses embraced by researchers. For instance, a study by Cao et al. (2014) investigated the influence of only the isomorphic pressures (i.e., Coercive, mimetic, and normative pressures) in isolation from other factors (i.e., innovation characteristics and internal characteristics).

This paper aims to investigate micro BIM adoption while overcoming these limitations. It considers BIM adoption as a complex system that is multi-staged and affected by several factors whose exerted influence on a specific adoption stage may change over time. To analyse such a system, the study adopts Systems Thinking Models. The System Thinking Models were heuristically developed by exploiting the results from two types of analysis: (1) statistical analysis (from Kassem and Ahmed, 2019) between the 11 top factors (as identified in Ahmed and Kassem, 2018) influencing BIM adoption in architecture practices; and (2) classification of the top factors in cause and effect factors and their interdependency analysis using the fuzzy decision making trial and evaluation laboratory (DEMATEL) method (from Ahmed and Kassem, 2019).

The resulting Causal Loop Diagrams (CLD) were used to profile adoption patterns both for the whole adoption process as a single system (i.e., without separating it into multiple stages) and for each individual stage (i.e. awareness, intention, and decision) over three time horizons (i.e. pre-2011 as the period preceding the announcement of the UK BIM mandate; 2011-2016 as the implementation and trial period; and post-2016 as the period following the mandate coming into effect). This paper describes only the patterns of BIM adoption as a single system. The CLD for this system included six key loops that are described in this paper.

3. Methodology and research methods

The top 11 factors (as identified in Ahmed and Kassem, 2018) influencing the BIM adoption process are used as an input into this study. These factors are: *Willingness to adopt BIM* (F1), *Communication behaviour of an organisation* (F2), *Observability of BIM benefits* (F3), *Compatibility of BIM* (F4), *Social motivations among organisation's members* (F5), *Relative advantage of BIM* (F6), *Organisational culture* (F7), *Top management support* (F8), *Organisational readiness* (F9), *Coercive pressures (Governmental mandate, informal mandate)* (F10), and *Organisation size* (F11) (Table 1). To achieve the aim of this study the findings of both the 'F-DEMATEL method' (i.e., Fuzzy Decision Making Trial and Evaluation Laboratory) (as in Ahmed and Kassem, 2019) (Table 2) – explained in next section - and the ‘correlation analysis’ (as in Kassem and Ahmed, 2019) (Table 3) will be used to develop the causal feedback loops as shown in the following sections.

Table 1 Definitions of the 11top influencing factors/ evaluation criteria of the F-DEMATEL

Factor	Definition
Willingness to adopt BIM (F1)	Refers to the favourable or unfavourable attitude of organisation or a decision-making unit towards the innovation/ BIM.
Communication behaviour of an organisation (F2)	The degree of openness and engagement of an organisation with social groupings and networks interested in innovation adoption and promotion.
Observability of BIM benefits (F3)	The degree to which the results from innovation/BIM adoption are visible and tangible.
Compatibility of BIM (F4)	The degree to which an innovation/BIM aligns with potential adopter’s previous experiences and current needs and values.
Social motivations among organisation's members (F5)	The motivation to engage in behaviours that benefit others such as considering others’ perspectives, stimulating knowledge exchange, and focusing on collective goals.
Relative advantage of BIM (F6)	The degree to which an innovation/BIM is perceived as being better than the system/practice it replaces.
Organisational culture (F7)	The shared norms, beliefs, principles, and traditions - held by the members of an organisational practice – which contribute to the members’ understanding of the organisational functioning.
Top management support (F8)	The degree to which senior management understands the importance of the innovation/BIM function and the extent to which they are involved into promoting the system adoption.
Organisational readiness (F9)	The extent to which organisational members are psychologically and behaviourally prepared to implement a change, their mutual determination to perform the change, and their mutual faith in their aggregate capacity to achieve the change.
Coercive pressures (Governmental mandate, informal mandate) (F10)	The formal and informal forces applied to organisations by other organisations (public and private clients/employers, etc.).
Organisation size (F11)	The total number of full-time members of staff of an organisation (e.g., micro, small, medium, and large).

Table 2 The F-DEMATEL results of the whole system of BIM adoption process (11 factors)

Factors	D	R	Defuzzified (D+R)	Rank	Defuzzified (D-R)	Cause/Effect
F1. Willingness to adopt BIM	0.529	0.743	1.272	11	-0.214	Effect
F2. Communication behaviour	0.594	0.678	1.272	3	-0.084	Effect
F3. Observability of BIM	0.597	0.559	1.156	2	0.038	Cause
F4. Compatibility of BIM	0.563	0.535	1.099	7	0.028	Cause
F5. Social motivations	0.554	0.611	1.164	9	-0.057	Effect
F6. Relative advantage of BIM	0.626	0.569	1.195	1	0.056	Cause
F7. Organisational culture	0.565	0.576	1.141	6	-0.011	Effect
F8. Top management support	0.555	0.694	1.249	8	-0.139	Effect
F9. Organisational readiness	0.582	0.576	1.158	5	0.006	Cause
F10. Coercive pressures	0.592	0.444	1.036	4	0.149	Cause
F11. Organisation size	0.553	0.325	0.878	10	0.228	Cause

Table 3 Set of 39 pairs of strong positive relationships among the 11 most influencing factors

Rank	Pair of correlated factors	Correlation value (rs, p)
1	Social motivations ⟺ Organisational culture	(rs= .503, p=.000)
2	Relative advantage ⟺ Observability	(rs= .418, p=.000)
3	Relative advantage ⟺ Organisational culture	(rs= .382, p=.000)
4	Social motivations ⟺ Willingness	(rs= .373, p=.000)
5	Observability ⟺ Communication behaviour	(rs= .368, p=.000)
6	Compatibility ⟺ Communication behaviour	(rs= .349, p=.000)
7	Organisational culture ⟺ Willingness	(rs= .336, p=.000)
8	Organisational culture ⟺ Organisation size	(rs= .336, p=.000)
9	Relative advantage ⟺ Social motivations	(rs= .308, p=.000)
10	Social motivations ⟺ Organisation size	(rs= .302, p=.000)
11	Observability ⟺ Top management support	(rs= .297, p=.000)
12	Top management support ⟺ Willingness	(rs= .295, p=.000)

13	Relative advantage ⟺ Organisational readiness	(rs= .283, p=.000)
14	Organisational readiness ⟺ Willingness	(rs= .282, p=.000)
15	Organisational readiness ⟺ Organisational culture	(rs= .282, p=.000)
16	Compatibility ⟺ Observability	(rs= .280, p=.000)
17	Top management support ⟺ Social motivations	(rs= .280, p=.000)
18	Top management support ⟺ Communication	(rs= .277, p=.000)
19	Communication behaviour ⟺ Social motivations	(rs= .273, p=.000)
20	Observability ⟺ Organisational culture	(rs= .267, p=.000)
21	Compatibility ⟺ Top management support	(rs= .255, p=.001)
22	Organisational readiness ⟺ Social motivations	(rs= .249, p=.001)
23	Willingness ⟺ Organisation size	(rs= .244, p=.001)
24	Communication behaviour ⟺ Organisational	(rs= .239, p=.001)
25	Organisational readiness ⟺ Organisation size	(rs= .238, p=.001)
26	Relative advantage ⟺ Communication behaviour	(rs= .236, p=.002)
27	Compatibility ⟺ Organisational readiness	(rs= .235, p=.002)
28	Relative advantage ⟺ Willingness	(rs= .230, p=.002)
29	Observability ⟺ Willingness	(rs= .221, p=.003)
30	Top management support ⟺ Organisation size	(rs= .217, p=.004)
31	Observability ⟺ Social motivations	(rs= .215, p=.004)
32	Top management support ⟺ Organisational	(rs= .214, p=.004)
33	Relative advantage ⟺ Organisation size	(rs= .214, p=.004)
34	Observability ⟺ Organisation size	(rs= .198, p=.008)
35	Communication behaviour ⟺ Coercive pressures	(rs= .176, p=.019)
36	Relative advantage ⟺ Compatibility	(rs= .165, p=.028)
37	Top management support ⟺ Organisational culture	(rs= .165, p=.028)
38	Communication behaviour ⟺ Willingness	(rs= .162, p=.031)
39	Observability ⟺ Organisational readiness	(rs= .162, p=.031)

4. Systems Thinking Model of BIM Adoption Process

This section describes the development of the systems thinking model which is used to establish the causal loop diagrams involved in organisational BIM adoption within the UK Architecture sector. This model captures the interrelationship between factors affecting BIM adoption; it helps in understanding how intra-organisation BIM adoption and diffusion occur, and how the organisations make the decision to adopt BIM. Causal-Loop Diagramming (CLD) is used to illustrate these chains of causal relationships among the factors affecting the BIM adoption process (i.e., system).

The CLD is based on the key variables (i.e., factors) of the systems whose interrelationships are critical to the system interpretation since they describe its dynamics (Suprun et al., 2016). The CLD also provides an additional visual comprehension of the current systemic relations among the system's components (Suprun et al., 2016; Richardson, 1986).

Constructing a causal-loop diagram (CLD) entails combining and integrating certain sets of input information (Suprun et al., 2016). Hence, the findings of both the 'F-DEMATEL method' (as in Ahmed and Kassem, 2019) (Table 2 and Figure 1) and the 'correlation analysis' (as in Kassem and Ahmed, 2019) (Table 3) were incorporated to illustrate and depict the causal feedback loops. The F-DEMATEL was used to classify the adoption factors into cause and effect factors and to identify such cause-effect factors between pairs of factors. The results are detailed in (as in Ahmed and Kassem, 2019). The correlation analysis was performed using Spearman's rank correlation coefficient analysis with a two-tailed significance test and helped identify the correlations between 11 most influential adoption factors. These correlations are summarised in Table 3.

Building upon these previous results, this paper describes the profiling patterns of BIM adoption which represents the behaviour of organisation when transiting from a pre-BIM (pre-awareness) status, through formulating the intention to adopt, to making the decision the decision to adopt. This study addresses this scope by considering the BIM adoption process as a holistic system without separating it in its constituent sub-stages and without considering different time horizons. To develop the CLD for such a system, the causal relationships among the factors (i.e., the causal diagram/digraph and the impact relation map in Figure 1) identified in the F-DEMATEL were collectively combined in multiple links that formed the feedback loops. From the correlation analysis, the resultant 39 pairs of strong relationships were used to identify the polarity of the formed feedback loops. A causal arrow between two factors indicates the direction of the change between the cause-effect pair. The polarity is denoted by (+) when two interrelated factors increase or decrease together, and by (-) when one of them increases while the other decreases. Also, a CLD may include two types of feedback loops: Reinforcing (R) loop, when two factors influence each other by two opposite (+) arrows; and Balancing (B) loop, when one arrow is (+) and the other is (-) or vice versa. Some causal link arrows may have marked with two hash (||) which denote 'delay' referring to the state when the effect takes time before it comes into place. Due to the complicated nature of interrelations among the factors of the developed system, it would be impractical and unfeasible to consider influence at all levels. Hence, this study has adopted a widely used approach in the literature (as in López-Ospina et al., 2017; Carpitella et al., 2018) which establishes a threshold value for the influence as an exclusion criterion and to avoid taking into account negligible effects. This threshold is calculated as the average of all the elements in matrix T (of the DEMATEL).

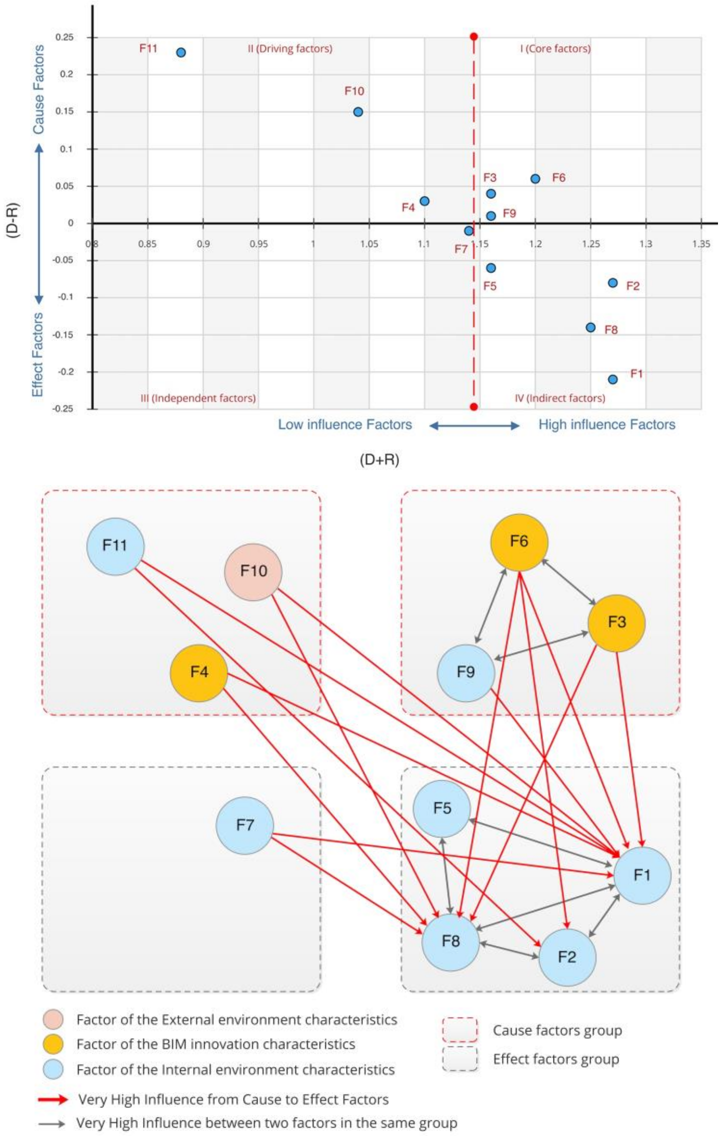


*Figure 1 (**bottom**) Impact Relation Map depicting cause and effect relationships and interdependencies among leading factors affecting BIM adoption; (**top**) Adoption factors classified in cause and effect factors*

In this case the threshold is 0.052. Moreover, this study focusses on the loops starting with a cause factor (i.e., identified in Quadrants I and II of the Impact Relation Map in the DEMATEL analysis) as this helps to address both the usefulness and the readability of the results. The systems thinking model focusses on the ‘Decision to adopt BIM’ as an outcome and aims to analyse the independencies between factor that lead to such an outcome.

5. Causal Loop Diagrams of BIM Adoption Process

This section demonstrates the possible CLDs that describe the BIM adoption process within the UK Architecture practices. The reported loops are those: including relationships above the influence threshold level (i.e., 0.052) adopted in the DEMATEL analysis; starting with a cause factor as identified in the DEMATEL’s Digraph (Figure 1b) and involving the highest number of interrelated variables/factors within each loop. Figure 2 shows six reinforcing loops (i.e., positive feedbacks) that are denoted by R1, R2, R3, R4, R5, and R6. The first four loops (i.e., R1, R2, R3, R4) start with the *cause group (influencing factors)* which are Relative advantage of BIM (F6), Observability of BIM (F3), Organisational readiness (F9), and Compatibility of BIM (F4), respectively. These factors were identified in quadrants I and II in the digraph of the F-DEMATEL (Figure 1b). The other two loops (i.e., R5, R6) also influence, through their effect factors [i.e., Willingness/ intention to adopt BIM (F1) and Social motivations among organisation's members (F5), respectively], the decision to adopt BIM. These loops can be explained as follows:

Loop R1 (i.e. entitled ‘Benefits of BIM innovation’) suggests that organisational readiness can be promoted by persuading senior managers about the anticipated benefits of adopting BIM (*Table* 4). This loop indicates that improving the perceived benefits obtained from adopting BIM (F6) stimulate the intention of the potential adopter to adopt BIM (F1). In turn, this contributes to an increase in the shared norms, beliefs, and traditions (F7) held by the members of the organisational practice. These shared values are reflected by the motivation of the organisation’s members who increase their engagement in behaviours that benefit others (e.g., stimulating knowledge exchange, and focusing on collective goals) (F5). These higher social motivations lead to increased openness and engagement of the organisation with social groupings and networks interested in BIM adoption and promotion (F2). Such communication behaviours improve the observability of BIM from successful BIM adoption (F3). Higher visibility of BIM benefits improves the perception of BIM as an innovation that is aligned with the potential adopter’s previous experiences and current needs and values (F4) which in turn, invites more executive support (F8). The support from senior management nurtures the organisation members' psychological readiness to implement BIM and their mutual determination to perform the change (F9). This, in turn, reinforces the perceived benefits obtained from adopting BIM (F6) (Figure 2 and *Table* 4). Other loops (R2 to R6) are summarised in Table 5.

Table 4 Loop R1 explaining the causal chain leading to the decision to adopt BIM by Organisations

Loop	Loop name	Interdependent factors	Indication
R1	Benefits of BIM innovation	Relative advantage of BIM (F6) ⟶ Willingness/ intention to adopt BIM (F1) ⟶ Organisational culture (F7) ⟶ Social motivations among organisation's members (F5) ⟶ Communication behaviour of an organisation (F2) ⟶ Observability of BIM benefits (F3) ⟶ Compatibility of BIM (F4) ⟶ Top management support (F8) ⟶ Organisational readiness (F9) ⟶ Relative advantage of BIM (F6).	BIM benefits can lead through its influence on a number of organisational characteristics (willingness to adopt BIM, organisational culture, social motivation, and communication behaviour) to an appreciation of the benefits of BIM and its compatibility, hence, inviting top management support which improve the organisation readiness and lead to the decision to adopt BIM.

Figure 3 shows a tree diagram that provides a simplified visualisation and analysis of model dynamics. It shows in a single direction which variables cause a particular variable to change. This representation captures the several intersections between the CLDs identified earlier. Only two levels are represented in Figure 3 but these could be extended to represent the whole CLD as a tree diagram. These simplified causal chains, when they are followed from the left to the right side, show how the decision to adopt BIM is reached within organisations.

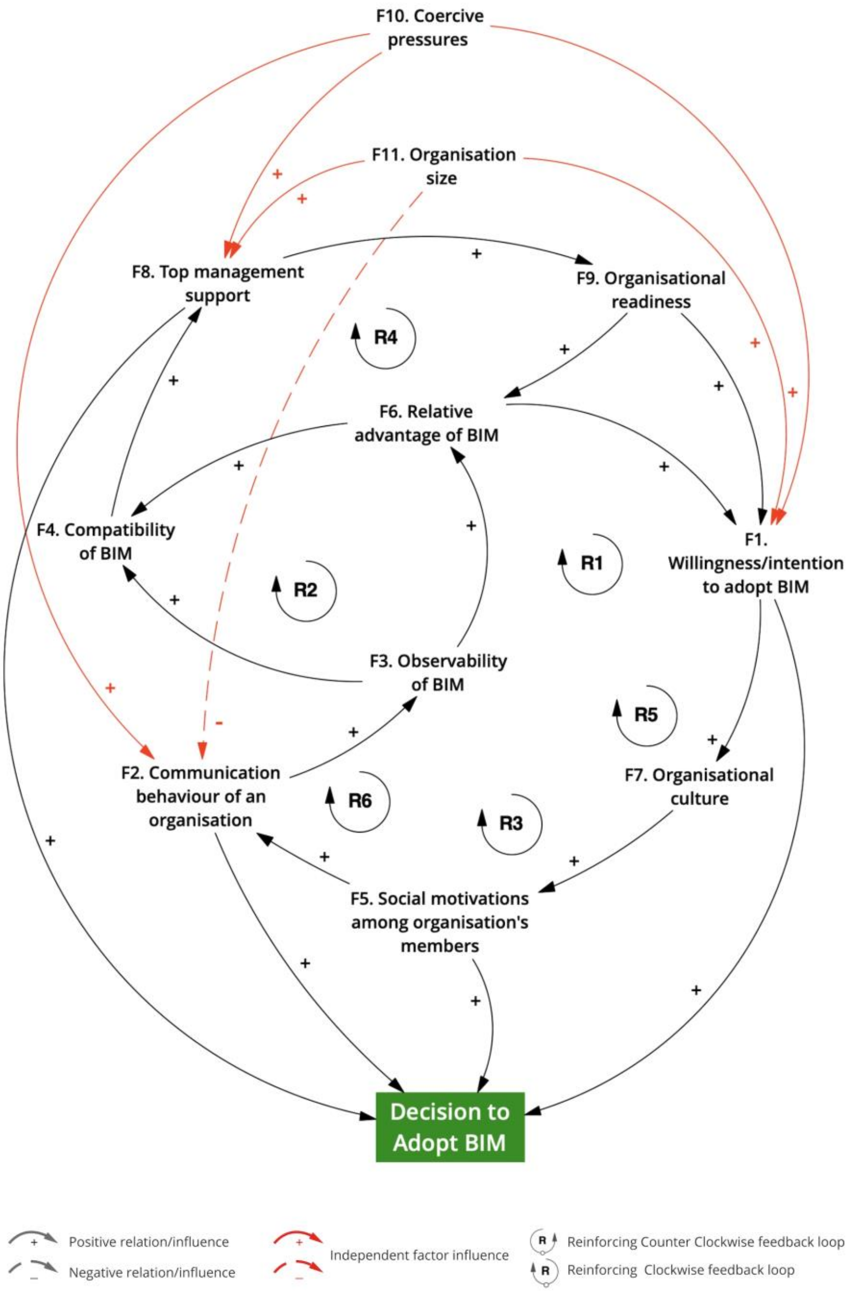


Figure 2 The Systems Thinking Model of Whole BIM Adoption Process (time-independent)

Table 5 Loops explaining the causal chain leading to the decision to adopt BIM by Organisations

Loop	Loop name	Interdependent factors	Indication
R2	Visibility of BIM benefits	Observability of BIM benefits (F3) ⟶ Relative advantage of BIM (F6) ⟶ Compatibility of BIM (F4) ⟶ Top management support (F8) ⟶ Organisational readiness (F9) ⟶ Willingness/ intention to adopt BIM (F1) ⟶ Organisational culture (F7) ⟶ Social motivations among organisation's members (F5) ⟶ Communication behaviour of an organisation (F2) ⟶ Observability of BIM (F3).	The more visible and tangible the BIM benefits to an organisation, the more the organisation perceives BIM as a compatible innovation. BIM compatibility in turn invites top management support that reflects upon their willingness to adopt BIM whose effect sequentially cascade down through a number of organisational characteristics (F7, F5, and F2) reinforcing the visibility of BIM benefits, and resulting in the organisation making the decision to adopt BIM.
R3	Organisational readiness to perform a change	Organisational readiness (F9) ⟶ Willingness/ intention to adopt BIM (F1) ⟶ Organisational culture (F7) ⟶ Social motivations among organisation's members (F5) ⟶ Communication behaviour of an organisation (F2) ⟶ Observability of BIM benefits (F3) ⟶ Relative advantage of BIM (F6) ⟶ Compatibility of BIM (F4) ⟶ Top management support (F8) ⟶ Organisational readiness (F9).	The organisation members' mutual determination to implement a change has a cascading effect, channelled through a number of organisational characteristics (F1, F7, F2) and innovation characteristics (F3, F6, and F4), on senior management support which reinforces the organisational readiness, and results in the organisation making the decision to adopt BIM.
R4	Aligning BIM with experiences and needs	Compatibility of BIM (F4) ⟶ Top management support (F8) ⟶ Organisational readiness (F9) ⟶ Relative advantage of BIM (F6) ⟶ Compatibility of BIM (F4)	The alignment of BIM with current and future needs helps to secure top management support which in turn improve the readiness of the organisation to adopt BIM. This in turn increase the perceived benefits of BIM which reinforces its compatibility resulting in the in the organisation making the decision to adopt BIM.
R5	Shared norms and beliefs among organisation' members	Organisational culture (F7) ⟶ Social motivations among organisation's members (F5) ⟶ Communication behaviour of an organisation (F2) ⟶ Observability of BIM benefits (F3) ⟶ Relative advantage of BIM (F6) ⟶ Willingness/ intention to adopt BIM (F1) ⟶ Organisational culture (F7)	Shared norms and beliefs among the members of the organisation help the organisation members engage in behaviours that promotes common goals. This in turn reflects upon openness and engagement of the organisation with social groupings and networks interested in BIM innovation adoption and promotion. Subsequently, this leads to improved visibility of BIM benefits by the organisation and an understanding of its relative advantage which further reinforces the shared norms and beliefs among the organisation's members, and lead to the decision to adopt BIM.
R6	Organisational communication behaviour with BIM-centric social networks	Communication behaviour of an organisation (F2) ⟶ Observability of BIM benefits (F3) ⟶ Relative advantage of BIM (F6) ⟶ Willingness/ intention to adopt BIM (F1) ⟶ Organisational culture (F7) ⟶ Social motivations among organisation's members (F5) ⟶ Communication behaviour of an organisation (F2)	Engaging in behaviours that benefit others (e.g., stimulating knowledge exchange, and focusing on collective goals) can be motivated by expanding the organisation's involvement with social networks interested in adopting BIM to understand its benefits, and can lead to the organisation making the decision to adopt BIM following a causal chain combining innovation characteristics (F3 and F6) and organisation characteristics (F1, F7, and F8).

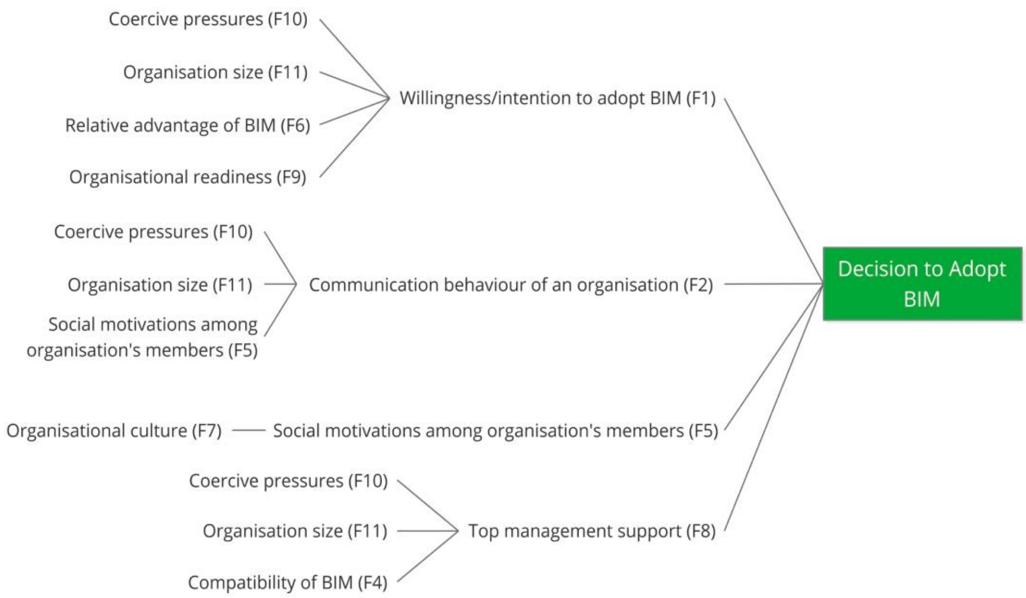


Figure 3 Tree diagram showing causal chains leading to the 'decision to adopt BIM' (time-independent)

6. Discussions and Conclusions

All the identified six feedback loops contribute to the organisational decision to adopt BIM by including a causal effect on four factors: willingness to adopt BIM (F1), communication behaviour of an organisation (F2), social motivations among organisation's members (F5), and top management support (F8). In addition to these six loops, some additional contribution to the decision to adopt BIM comes from certain independent factors and it is important to be highlights. In particular, two independent factors [i.e., Coercive pressures such as governmental mandates and client informal mandate/expectation), and organisation size (F11)] have a contributing effect on the decision to adopt BIM through their direct influence on some of the four effect factors (i.e., F1, F2, and F8). Greater coercive pressures (as either governmental mandate, or industry and client expectation/requirement) (F10) help inducing a favourable change towards BIM adoption through changes in: the willingness to adopt BIM (F1), communication behaviour of an organisation (F2), and the top management support (F8). The organisation size (i.e., micro, small, medium, and large) has a varying influence on specific factors. For example, larger organisations, compared to small organisations, have more willingness to adopt BIM, enjoy more senior management support, and are characterised by limited openness and engagement with social groupings and networks interested in innovation adoption and promotion.

The six feedback loops that resulted from the CLD model of the whole BIM Adoption Process (time-independent) represent the prominent profiling patterns of the behaviour that drive organisations to adopt BIM. These patterns can help in analysing, understanding, and informing tailored policies, and action plans for micro BIM adoption within the architectural sector, when links are made between the driving factors involved in each of the loops/patterns and the implementation activities. As a result, this model contributes to promote BIM adoption by clarifying the dynamics and patterns underpinning the BIM adoption process while focussing on the leading drivers for adoption: the benefits of BIM innovation (Loop R1), visibility of BIM benefits (Loop R2), organisational readiness to perform a change (Loop R3), aligning BIM with experiences and needs (Loop R4), shared norms and beliefs among an organisation' members (Loop R5), and Organisational communication behaviour with BIM-centric social networks (Loop R6). The future extension of this work will aim to create links between these leading adoption factors and the industry stakeholders' groups. Implementation activities that can be exerted by each industry stakeholder group on these leading adoption factors will be used to create such links.

Acknowledgements

This work has been sponsored by the Iraqi Ministry of Higher Education and Scientific Research (MOHESR) jointly with the University of Technology, Baghdad, Iraq.

References

AHMED, A. L. & KASSEM, M. 2018. A unified BIM adoption taxonomy: Conceptual development, empirical validation and application. *Automation in Construction,* 96**,** 103-127.

AHMED, A. L. & KASSEM, M. 2019. Micro BIM Adoption: Identifying Cause and Effect Factors and Analysing Inter-dependencies Using a Fuzzy DEMATEL Approach. *Proceedings of the Creative Construction Conference (CCC2019).* Budapest, Hungary.

AL-SHAMMARI, M. A. An appraisal of the protocol that was published by the Construction Industry Council (CIC) to facilitate the use of Building Information Modelling (BIM) on projects. *In:* RAIDEN, A. & ABOAGYE-NIMO, E., eds. 30th Annual Association of Researchers in Construction Management Conference, ARCOM 2014, 2014. Association of Researchers in Construction Management, 623-632.

ATTARZADEH, M., NATH, T. & TIONG, R. L. K. 2015. Identifying key factors for building information modelling adoption in Singapore. *Proceedings of Institution of Civil Engineers: Management, Procurement and Law,* 168**,** 220-231.

CAO, D., LI, H. & WANG, G. 2014. Impacts of isomorphic pressures on BIM adoption in construction projects. *Journal of Construction Engineering and Management,* 140.

CARPITELLA, S., CARPITELLA, F., CERTA, A., BENÍTEZ, J. & IZQUIERDO, J. 2018. Managing Human Factors to Reduce Organisational Risk in Industry. *Mathematical and Computational Applications,* 23**,** 67.

GHOLIZADEH, P., ESMAEILI, B. & GOODRUM, P. 2018. Diffusion of Building Information Modeling Functions in the Construction Industry. *Journal of Management in Engineering,* 34**,** 04017060.

HARON, A. T., MARSHALL-PONTING, A., MOHD NAWI, M. N. & ISMAIL, M. H. 2014. Building information modelling:A case study approach to identify readiness criteria for process requirement. *American-Eurasian Journal of Sustainable Agriculture,* 8**,** 85-91.

HOSSEINI, M. R., BANIHASHEMI, S., CHILESHE, N., NAMZADI, M. O., UDEAJA, C., RAMEEZDEEN, R. & MCCUEN, T. 2016. BIM adoption within Australian Small and Medium-sized Enterprises (SMEs): an innovation diffusion model. *Construction Economics and Building,* 16**,** 71-86.

KASSEM, M. & AHMED, A. L. 2019. Micro BIM adoption: A Multi-dimensional Model Profiling BIM Adoption in Architectural Practices. *Proceedings of the Creative Construction Conference (CCC2019).* Budapest, Hungary.

LÓPEZ-OSPINA, H., QUEZADA, L. E., BARROS-CASTRO, R. A., GONZALEZ, M. A. & PALOMINOS, P. I. 2017. A method for designing strategy maps using DEMATEL and linear programming. *Management Decision,* 55**,** 1802-1823.

RICHARDSON, G. P. 1986. Problems with causal-loop diagrams. *System dynamics review,* 2**,** 158-170.

ROGERS, E. M. 2003. *Diffusion of Innovations, 5th Edition*, Free Press.

SUCCAR, B. & KASSEM, M. 2015. Macro-BIM adoption: Conceptual structures. *Automation in Construction*, 57**,** 64-79.

SUPRUN, E., SAHIN, O., STEWART, R. A. & PANUWATWANICH, K. 2016. Model of the Russian Federation construction innovation system: An integrated participatory systems approach. *Systems*, 4**,** 29.

TANG, X. L. & YI, X. H. BIM technology diffusion study in construction enterprises based on Bass model. 2015 2nd International Conference on Machinery, Materials Engineering, Chemical Engineering and Biotechnology, 2015. Atlantis Press.

Automation of data transfer between a BIM model and an environmental quality assessment application.

Adam Piaskowski[1*], Reinis Petersons[1], Simon Christian Swanström Wyke[1], Ekaterina Petrova[1] and Kjeld Svidt[1]
[1]Department of Civil Engineering, Aalborg University, Denmark
*email: akptech@outlook.com

ABSTRACT

Automating the transfer of Building Information Model (BIM) data to assess energy performance is still far from straight forward. The approach of using Industry Foundation Classes (IFC) or Green Building Extensible Modelling Language (gbXML) is only justified if the parametric data is accurate and explicit and if the designers are proficient at console coding. Mapping parameters to rigid schemas and calculating quantities and volumes can be time-consuming and require software engineering knowledge. Using Action Research Methodology, two student groups investigate methods of data transfer and parametric data derivation process. To ensure correct data transfer, we propose an API-based proprietary pre-computation which connects Revit objects and parameters with an Excel-based Indoor Environment Assessment tool (IV20). IV20 is currently under development at Aalborg University, and it serves us as a set of Business Rules, defining required inputs needed for an energy assessment. This case study focuses on automating features that perform extraction, calculation, and storage of input data, based on a set of predetermined user requirements. Dynamo Visual Programming Language (VPL) is used to extract sample information regarding room and element properties, façade orientations, and building surroundings. We conclude that Revit-Dynamo-Excel (RDE) approach can significantly automate data transfer, but it requires explicitly modelled objects, agreed exchange requirements, and a well-defined and communicated calculation method. Our approach does not eliminate IFC interoperability, but rather enhances the proprietary model information advancement, prior to export.

Keywords: BIM, data transformation, data exchange, visual programming, indoor environmental quality

1. INTRODUCTION

The Danish government has put a significant effort in promoting the sustainable renovation of existing buildings, placing a strong emphasis on the improvement of indoor environmental quality, building energy performance, and occupants' comfort (Gram et al, 2010; REBUS, 2015; Harrestrup & Svendsen, 2015). When renovating buildings, it is necessary to ensure satisfactory living conditions, and evaluate the building state. This can be done by benchmarking its existing performance against modern building regulation requirements. Concurrently, Building Information Modelling (BIM) and modern surveying technologies have reshaped the renovation workflows and have allowed setting more accurate and efficient energy performance targets (Habibi, 2017). Semi-automation, when coupled with a definitive list of inputs and outputs can assist speedy delivery of a complete energy analysis cycle.

When designing a BIM application, the standardized process involves formulating Exchange Requirements (ER) by following international standards such as Industry Foundation Class (IFC) Information Delivery Manuals (IDM), and validating information exchange against Model View Definitions (MVDs), to ensure complete and correct data transfer. MVD's are used as holistic data subsets, validating that certain design elements are exchanged, specific to the intended use cases (Borrmann, König, Koch, & Beetz, 2018). ER can also follow custom-made standards such that follow a structure as the British BIM Protocol Employers Information Requirements (EIR) (CIC, 2013).

While the ERs are key to defining case specific inputs and outputs for energy analysis, further action towards IFC software validation against MVDs does not share its intended specificity, as the subsets are wide and generic, and released in only a few versions (Pinheiro et al., 2018). This process may work for big software vendors, well acquainted with using MVDs, but for quick analysis between specific stakeholders, this can cause inconsistencies and costly project delays. There seems to be a need for a simpler, more commonly communicated workflow, which is based on standardized principles, yet is flexible and easily implementable directly by design consultants, without the need of expensive validation methods. Although we aspire to find an effective workaround to the complexity of using Model View Definitions (MVDs), we follow the standardized Exchange Requirements (ER) workflow, proposed by the buildingSMART ISO 16739-1:2018 standard for BIM information exchange (ISO, 2018).

Validation, coupled with the rigidity of IFC schema, regional versioning, and holistic MVD's opens a window of opportunity for an alternative workflow using tools currently familiar to the industry professionals, who are often not fluent in console coding. It is why we propose to use Dynamo Revit, as a tool capable of extracting, calculating and linking building elements' properties and attributes, to MS Excel spreadsheets. We thereby aim to contribute to the subject of data transfer, by using Visual Programming Languages, instead of console coding.

The reason for choosing Microsoft Excel is its maturity and widespread adoption as a preferred file-based database tool. Similarly, the wide adoption of Autodesk Revit has placed the software amongst most popular BIM authoring tools (Eastman, 2016). Even if IFC MVDs will become more customizable and simpler to implement, Revit workflows will still be applicable as BIM authoring tools. As neutral formats i.e. *.ifc* are inadequate to re-create the native formats, the neutral formats must be augmented by native formats such as *.rvt* for Revit (Borrmann et al., 2018).

Alternative workflows proposed by Kamel & Memari, (2019) require the user to export a file in gbXML format. Pinheiro et al., (2018) recognizes the use of IFC4, after identifying that gbXML uses only centreline representation for geometry area calculations. These processes, although derived from IFC, require 3rd party software specializing in building energy analysis, such as Modelica or EnergyPlus, which must be purchased on top of the authoring tool. Using data structured in standardized IFC schema, Bazjanac (2008) recognized the need for small workarounds as amongst other issues, data content may need simplification prior to extraction.. Using IFC4 and Modelica can result in bottlenecks when using IFC for Building Energy Design, identifying a need for custom MVDs (Andriamamonjy, Saelens, & Klein, 2018). All the above methods rely on proprietary geometry, deriving from software such as Autodesk Revit. As a result, regardless of file format, data from proprietary authoring software will always be utilized to inform later design stages.

It is rarely the case that geometry data from Revit is ready for IFC export (Kassem, Kelly, Dawood, Serginson, & Lockley, 2015), regardless of Level of Detail. When creating Revit models, default Revit quantities are often calculated inaccurately or follow undesirable calculation assumptions. Ensuring information validity can be challenging, and therefore it is important to identify information requirements and calculation methods before exporting data values for energy analysis. As data input for energy assessment stems directly from Revit geometry, and the geometry can be modelled to a varied level of detail, in multiple ways and with varied parameter naming, attention is brought to following standard processes. Due to a diversity of project participants with varied BIM knowledge, even experienced Revit users make mistakes when transferring information to other professionals outside of their own expertise.

There are ways to ensure that the information agreed in ER is complete. Following IFC standardized workflow, a well-defined Information Delivery Manual can explicitly specify information content, geometry content, data types, attributes, attribute and object naming, level of detail, and other project-specific principles. IDM guidelines (Wix & Karlshøj, 2010), though specified to support IFC workflow, are a relevant tool when deriving non-IFC based Exchange Requirements. Alike IFC, proprietary models can be validated against Exchange Requirements both by the sender and the recipient of BIM data. Exchange Requirements consistency checks are there to ensure the information transfer is valid, and in the event of missing information, the cost incurred is correctly assigned to the party responsible for error correction. Although information validation is not a part of this article, Dynamo functionality can be utilized to pre-validate, and post-validate ER parameter content.

Having a set of in-house Dynamo scripts can help an architect, or an energy consultant, verify if the model can be used for energy simulation. Creating uniformly named parameters is necessary for mapping to be permanent. Dynamo, by plugging directly to Revit API (Borrmann et al., 2018), can link model data with MS Excel in real-time. Dynamo Visual Programming Language (VPL) is using nodes which act as pre-defined code-blocks with built-in functionality and direct connectivity to the opened Revit project.

VPLs differ on their level of granularity. The more granular, the higher the detail of data processing visible to the user, at a trade-off of increased complexity. Dynamo Revit allows a user to use nodes ranging from single values such as strings or integers to complex combinations of code consisting of many sub-nodes. Dynamo Revit environment, although a part of Revit – a licensed software, imitates to some extent an open-source community, by embracing knowledge sharing ("What is Dynamo? | The Dynamo Primer," 2018).

The data can be stored within Revit parameters, or in an external database such as dRofus ("Home | dRofus," 2019)or MS Excel, and extracted when needed. Furthermore, necessary parameters that fit IFC schema can be exported from Revit to IFC standard MVD such as IFC2x3 Coordination View 2.0 (Building SMART, 2018), for further analysis. Therefore, our approach does not eliminate IFC interoperability, but rather enhances the proprietary information advancement, prior to export.

2. METHODS AND PROCESSES

The case study is based on Action Research Methodology (Bryman & Bell, 2011). Aalborg University is developing a thermal assessment tool called IV20 (REBUS, 2015), which aims to holistically assess a range of indoor environmentally related standards regarding thermal, visual, atmospheric and acoustic comfort. In order to reduce the time it takes to manually input energy performance data, two test groups were given a task to investigate how can Dynamo enable parameter value calculation and automate information transfers between a BIM model and Excel IV20. The Exchange Requirements were defined by the input parameters of IV20 and prototyping and testing was investigated by the two test groups. We compared the accuracy of the answers to manual methods and attempted to automate the calculations needed for parameter transfer using Dynamo VPL. We wrote several scripts to compare how they perform on varied geometry conditions. As the two groups worked on the same Exchange Requirements, at least two methods were developed to calculate the same parameters. The methods were then compared, and the results and observations are described in this article.

The essential objective of Revit-Dynamo-Excel (RDE) workflow is to reduce transfer process complexity, target specific parameters, and establishing data extraction and calculation methods. The 6 rules below describe processes necessary, prior to creating the Dynamo scripts:

1. Parameter domains and rules need be defined in the Exchange Requirements.
2. Calculation methods need be explicit and delimited to their application, i.e. calculations for straight walls will differ from calculations for slanted walls.
3. The Revit model geometry must be modelled to the agreed level of detail.
4. The Revit model must be specified to an appropriate level of information.
5. The Revit model must be verified and validated prior to information takeout.
6. All models sharing the same phase and geometric properties of the first concept must follow the same naming conventions and rules for the scripts to be effective on other projects.

The success of energy calculation greatly relies on the calculation method and preliminary data derived from the Revit model objects. The methodology assumes that the model contains architectural objects needed for initial energy calculation and that the modelling method is following a structured workflow.

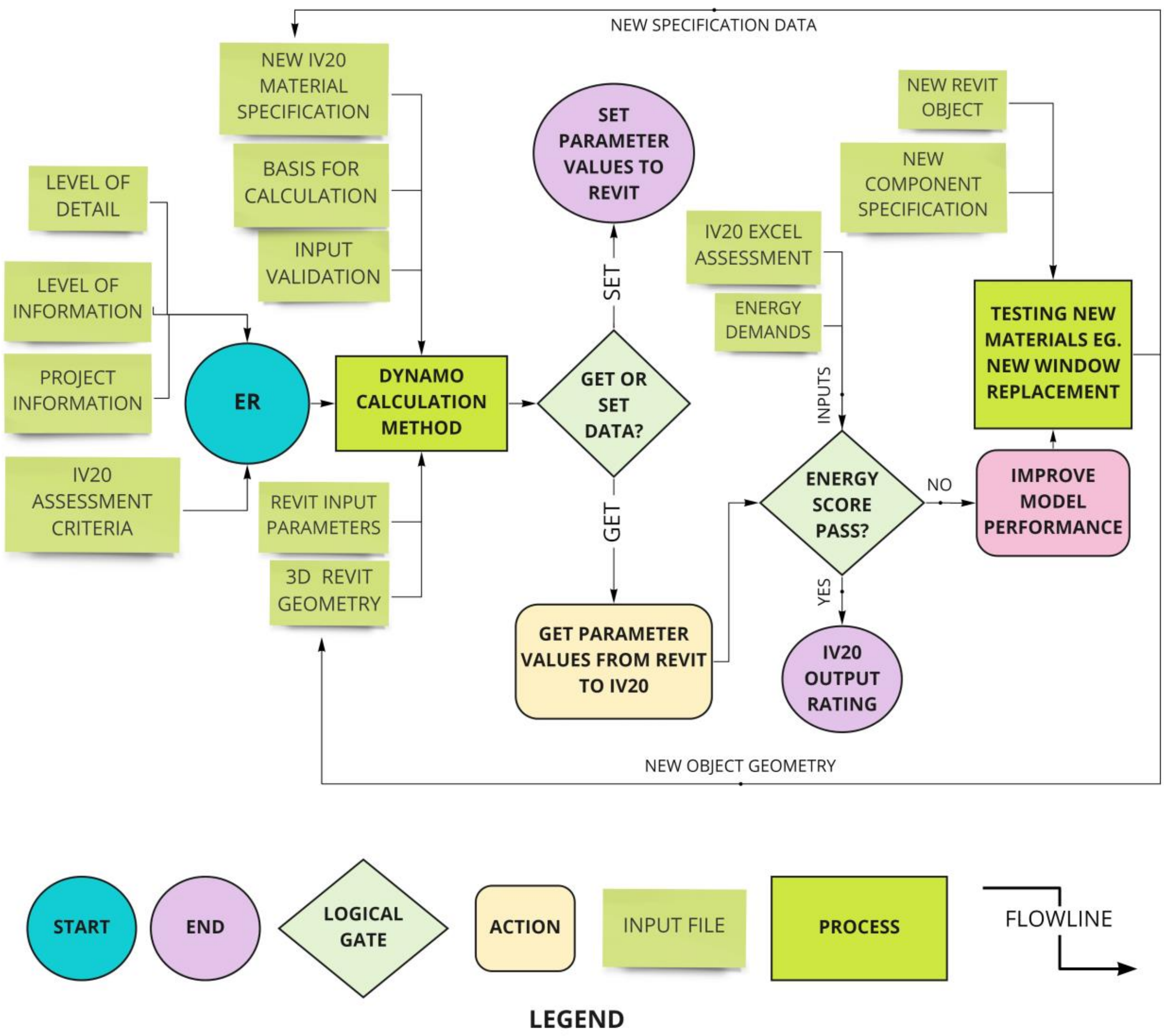


Figure 1 Process diagram of RDE workflow.

3. PROTOTYPES FOR PRACTICAL APPLICATIONS

In this section, we will look more closely into Dynamo VPL as a calculation and data transfer tool. We will attempt to describe calculation methods and processes so that the reader can learn techniques we developed. When deriving parameter values, considerations need to be noted down, to allow future scripts users to be aware of script applications and limitations.

Just like when analysing an object visually, a computer must understand what the object representation means to a certain script. For example, it is simple for a person to understand the difference between an internal and an external wall, provided there is a window with a view out. A computer can assess whether the wall is external, only if the wall property contains a parameter that specifies its function - to *exterior*. All walls in Revit of the same type will have a specified function, meaning their function is a *type* property. It is therefore detrimental, the Wall type is set correctly so that Dynamo can reason, whether the wall is *exterior* or *interior*.

It is a good idea to create a set of steps for each script, guiding its logic and chronology of creation. Below is a sample chronological workflow, paving a way for wall area script determination.

1. Exporting wall and room information from the Revit model.
2. Measuring the lengths of wall segments for each room.

3. Mapping segment lengths to specific wall instances.
4. Summing wall instances and multiplying by room height to obtain area.
5. Excluding window and door areas from walls.
6. Listing results for each room instance.
7. Converting measurement units and rounding to agreed decimal points.
8. Translating results to a tabular form.
9. Exporting results to IV20.

3.1. GROUPING BY ROOM OBJECT ID

Although Revit Identifier (ID) is not the same as IFC Globally Unique Identifier (GUID), as its value can be altered when updating components, its use is justified when identifying components during live operations in Revit and Dynamo. It becomes especially useful, when Dynamo highlights the code in green, meaning the information transferred is a function, not a label (string value). It is, therefore, a good practice to keep track of element ID and storing it visibly within Revit object parameters throughout the period of operation. It can serve as a dynamic reference point, which updates along with holistic model updates, yet remains static, when element count, and file version remains constant. A node called *Element.Id* can extract the ID and append its string value to the desired parameter name. Lastly, selecting the element can lead a user directly to the location of the element within Revit, having a similar functionality of the BIM Collaboration Format (BCF) element selection zoom function.

This information can be later retrieved by using *Element.GetParameterValueByName* node. Other information can be retrieved, such as *Name*, *Area* and, *Volume*, given the parameter exists within the Room category. Once parameters are generated, the lists can be transposed to match tabular entry sorted by the desired filtering element. In this case by room name. This process will allow grouping elements by room, enabling selection of elements only relative to their spatial placement. *List.Transpose node* swaps or transposes columns with rows, thereby changing a list of i.e. room names, areas, and volumes, to a list of room names and their corresponding parameters i.e. areas and volumes.

Using the same principle, we assign room names to windows, in order to recognize the window location filtered by belonging room, and in the same way, we can assign other parameters to the window as described below. This way, we can create a hierarchy tree where the building is a container of rooms, and a room is a container of elements such as windows and doors. Further down, windows are containers of properties within windows. This way the hierarchy classification can follow the intended IV20 schema, and data can be published accordingly to desired work sheets.

A *Data.ExportExcel* node is used to send tabular data to Excel enabling the data to be stored natively in Excel Spreadsheet (.XLS), or if needed, in an interoperable format - Comma Separated Values (.CSV). The node takes inputs for Excel file path, sheet name, starting row and columns, the data desired for export, and a *Boolean* to override current data content. It has proven useful to detach the file path with the export node, as to prevent accidental data updates when running Dynamo scripts. Consequently, data override will wipe the entire sheet blanc and should be used with intent.

3.2. WALL SURFACE AREAS

It is ambiguous, whether the calculation principle considers discrepancies such as wall openings, ceiling height, and internal boundary condition offset. Wall surface areas can be misleading when directly taken from the Revit model. Using the *Room.Boundaries* node, we derive the *Curve.Length* calculation of boundary room edge length. This allowed us to retrieve wall lengths to measure internal surface wall areas – directly from automatically generated rooms within Revit. We then used the ceiling height parameter to derive wall heights up to the ceiling. Alternatively, if no ceilings are present, room height can be constrained to a different parameter, agreed in the IDM.

This flexible approach demands user attention, and therefore is semi-automatic, as the operator must know which parameter is responsible for limiting room height. Similarly, depending on use, a room boundary line can skew resulting perimeter length. There is a discrepancy in length between the inner, centre and outer wall perimeter. A formula for determining offset can be added using *codeblocks*.

Codeblocks are python based, console coding blocks, especially useful for mathematical formulas, reducing complexity and node granularity. A *codeblock* can merge an offset parameter relative to the wall centreline, by applying a correction to the perimeter length calculation.

Once the overall surface area is calculated, the following step involves excluding areas occupied by openings, such as doors and windows. There are a couple of methods to exclude those areas, and this process can be automated if the opening elements' properties, (i.e. location) can be segmented by Revit rooms. A node called *Room.IsInsideRoom* can be used to check if certain elements are a part of a room. This can, however, fail, if the elements are recessed into walls, and the room objects consider only elements within the room boundary lines. Again, there are multiple ways of addressing this fix, and the solution may vary depending on the method.

Using *Element.GetLocation* node and *FamilyInstance.FacingOrientation*, we created two intersecting points for each door and window element with a proximity offset of +/-300mm, perpendicular to the room boundary. This method has taken all intersecting door and window elements, which had a facing orientation parallel to the room boundary, placed within the *300mm* range. This ensured that regardless of the boundary location line, items in proximity were considered to the count. This enables a *Boolean* output from the aforementioned node called *Room.IsInside.Room*, which marks objects belonging to a room as *true*. The flattened list was then filtered by *List.FilterByBoolMask* to filter true values only.

Lastly, the *area parameter* was obtained from intersecting doors and windows and the value was subtracted from the total surface area of the walls within the room. It is important to observe here, that if the room did not contain any windows, a *null* value would produce a *null* result if the list was not cleaned by using *List.Clean* node and preserving indices set to *Boolean* "*false*". This ensured that any *null* values will be removed from the list, thus preventing strings to mix with numerical formulas.

3.3. WINDOW ORIENTATION TO TRUE NORTH

Window orientation is essential for energy analysis, as the information can identify the exposure to sun and external objects, as well as identify window location and the angle to true north. To populate orientation angles to external doors and windows, firstly, we select only exterior doors and windows. If curtain wall panels are present in the model the same principle applies to those elements. To select exterior elements, we can filter elements by "*Function*" parameter within *Element.ElementType* node. This is important when accessing element type properties, as the function is defined at a type, and not at an instance level. If we did not use the *Element.ElementType* node, only instance parameters list will show. Exterior elements function value is equal to *1*, as it is the second element on the list i.e. *0=Interior*, *1=Exterior*, mapping numbers to function displayed in Revit drop-down Element Type Function list. By default, in Python language, thus in Dynamo VPL, the first element of every list is indexed as *zero*.

List.Join is then used to join filtered lists of exterior curtain walls, exterior doors, and windows. To get the element orientation we used the *FamilyInstance.FacingOrientation* node and a custom node from Clockworks package called *Wall.Orientation*. Packages are sets of nodes created by the Dynamo community to enhance Dynamo off-the-shelf capability. Note that *Wall.Orientation* node checks orientations for walls only, but the doors and windows are elements nested within walls, and thereby their orientation is transferred as a result. The resulting list of walls and wall-nested family instances are joined by *List.Join* again.

The next step is to link Revit project rotation to define the angle to true north. We used the *Vector.Rotate* node, which took the resulting List.Join and used its vectors as its first input. The second input was the axis of rotation – the Z-Axis, obtained from the *Vector.ZAxis* node, and the third input were the project coordinates, obtained from the *Coordinates.ProjectRotation* node. In order to define true north, the project rotation needs to be negative. A simple *codeblock* subtracting Project Rotation from a value of *0* will suffice.

Our final input is provided in degrees and the *Vector.Rotate* node gives out a vector which can now alter vector angle about the axis. Using the *Vector.AngleAboutAxis* node, the *Vector.Rotate* is coupled with the second input of reverse Y-Axis vector, and a rotation axis around Z-Axis Vector. The resulting angles will give values ranging from *0* to *360 degrees*. It is a requirement that the value instead uses a scale from *-180* to positive *180 degrees*, thus a *ReplaceByCondition* node can append the result only for values above *180*, replacing the item with a formula which subtracts *360* from the original value. To validate true north rotation, it is important that the project location is set correctly to reflect real-world coordinates or that the site coordinates are published to the project from the Revit site link.

3.4. ROOM OVERSHADOWING

To check if overshadowing objects affect a room sun exposure, we calculate the parallel and perpendicular distances to adjacent buildings which limit sun exposure by providing desirable or undesirable shadow effects. The IV20 exchange requirement is expressed as *distance to shading object*. Given the proximate environment is geometrically modelled, using Dynamo, we select the closest face of the building and calculate the distance using the *Geometry.DistanceTo* node.

This action will require an operator to manually select faces, which may be very inefficient in projects containing multiple rooms. This process can be expanded by attributing faces to windows automatically, by mapping them to windows and mapping windows to rooms, as explained in section 3.1. This procedure would allow selecting a room, letting the programme know which window within the room is picked, and which surface represents the unobscured glass face of the window. Equally, by measuring the distance to multiple objects, it is possible to filter the shortest distance and append this measurement to the window face at hand. A loop can be created to check for all windows within a room, and all rooms within a project, and automatically derive distance measurements from each shading object. On top of distance to shading object, the IV20 required parameters specifying the height and inclination angle to of which, the building will cover the sun path, relative to its distance. We did not attempt to calculate these parameters due to time constraints, yet we suppose the calculation will follow similar principles to the above.

3.5. ROOM SURFACE MATERIALS

It is also possible to reverse the flow of information – and instead of populating IV20, materials can be specified from within IV20, and published to Revit. This is useful when communicating analysis results back to the design team. In order to calculate energy loss of the building, the materials of room closing elements – walls, ceilings, and floors must be recorded. In IV20, there are predefined nine types of rooms, six floor, eighteen wall, and fourteen ceiling materials, that can be mapped to Revit objects using MS Excel.

Plugging the *File path* to the IV20 spreadsheet enables reading data from Excel. We choose the sheet we want to read, and we mark *Read As Strings* with a *Boolean* set to true. We then transpose the list to obtain parameter values grouped by *Room Name* attribute. *List.RemoveFirstItem* can be used to remove list headers. We then choose the list index to match the list needed for floor finishes, wall finishes and ceiling finishes to match them to the Revit default parameters.

We then pick Revit rooms and match them with the IV20 Excel list. We make sure that the room list in Excel is matching the Room list in Revit, by using Room Element ID number. This ensures there are no two rooms having the same name. Lastly, we run the script and populate material information to Revit to set material data used for specific energy calculation in the form of a string parameter. Then the results can be observed inside of Revit schedules with the material information populated into each of the rooms. This process has a similar application to the BIM Collaboration Format used with IFC. Now that the information is populated, it is up to the design team to approve material changes.

4. OBSERVATIONS

In this study, we attempted to bridge some geometry data with a spreadsheet-based energy assessment tool, enabling a greater degree of automation of indoor environment assessment analysis. Dynamo scripting was used as the linking tool and observations had been made on how elements can be validated, calculated and translated to a spreadsheet. Not all parameters necessary for IV20 input were calculated, but each new script was a step closer towards more comprehensive automated data transfer.

The main purpose of this workflow was to develop a missing link between Revit model geometry and an MS Excel spreadsheet. The transfer will allow the IV20 tool to further analyze results and use the data to evaluate the indoor environment. As each calculation requires a specific approach, before all scripts are created and validated, one cannot fully rely on automating a specific task, as it may be based on incorrect quantities or methods. However, once the methods are validated, a significant improvement in quality and validity of data can be achieved.

Interpretation of models needs to be carefully analysed to yield appropriate and equivocal results. It is of major importance to agree on the level of detail and component specification, to ease, or at least bring to awareness that some object properties may be inaccurate. For example, area and volume values may be inaccurate due to built-in Revit calculation rules, placing boundary line in a different location than anticipated.

There are multiple ways of performing tasks within Dynamo, and more than one way can be correct. Explicit calculation method forms a foundation of rigid script development. Further script improvements reduce complexity and improve the transparency of the code, whilst keeping the clarity of formulas and calculations. A higher level of automation is accompanied at the trade-off of transparency, which is especially dangerous if the end-user was not involved in the creation of the scripts. Therefore, we advise that the in-house knowledge of Dynamo is shared across all involved stakeholders through commonly available standards and methodologies.

A good practice when attempting to design a new visual code script, is to create a logic map, describing issues that will be encountered during the calculation. A logic map can be communicated with the model provider using conceptual diagrams using UML or IDEF0, which clarify information flow, calculation principles and presumptions.

Although Dynamo requires some degree of programming knowledge, and a good understanding of the functionality of Autodesk Revit, thanks to the transparency of VPL interface and prompt response of Dynamo forum users, we found using Dynamo rewarding, and our understanding of the software had grown considerably in a short period of time. The community is active and keen on sharing ideas and is gladly offering help to solve problems. We discovered it a good idea to search for related issues before posting our own issues, and we observe that most computations had been encountered before, thereby enabling a short problem lifespan.

Dynamo scripts can be simplified as the user experience grows. Highly granular nodes can be compressed to blocks and calculation can be optimized by creating code-blocks. This can be done using custom nodes functionality, or by optimizing calculation techniques. For example, a curve length can be calculated as a distance between the start and end point, or a *Curve.Length* node can achieve the same, or even a more accurate result, as it will consider all curve points, allowing more widespread application, enabling calculating the length of curved elements.

5. CONCLUSION

We conclude that automation of data transfer is possible and achievable for industry professionals, using Dynamo as a data transfer link. The key advantage of using RDE workflow is relative simplicity, logarithmic learning curve and an in-house, software cost-reducing, development process. Additionally, unlike IFC information modelling, the data structure can be user-defined and calculated prior to IFC export. The data can be stored in use case specific parameters, that can be agreed upon using standard Exchange Requirements such as IFC IDM or EIR.

The Revit model geometry and parameters can be directly linked with MS Excel spreadsheet and the links can be sustained if the Revit models are modelled to the same level of detail, and following the same rules and parameter naming. However, to achieve a high degree of automation on a multitude of projects, thorough modelling and calculation standards need to be implemented across project stakeholders.

Knowledge transfer and transparency is key to script re-use and applicability in other projects. An in-house validation method needs to be developed, to ensure that Revit models are ready for reliable automatic data transfer when using Dynamo Revit. When creating Dynamo scripts, clear workflows must be in place, and parametric limitations must be clearly specified. Script operators must be aware of script limitations and principles under which the scripts perform calculations, prior to drawing assumptions that the quantities or information content is coherent. Although our attempts yielded accurate results, and we succeeded in deriving some key parameters, we did not attempt to link and calculate every IV20 parameter needed for a complete thermal, visual, acoustic and lighting assessment.

Not all data transfers were fully automatic. In some early prototypes, an operator needed to switch the room in question to publish the results or select an object face for analysis. As our experience grew, we managed to automate these processes, at the same time increasing script functionality. Therefore, it is difficult to estimate if each data transfer can be fully automated by an average Dynamo user, but we can safely say that persistent Dynamo programmers will be likely capable of programming any parameter derivation. The status quo of IV20 will require all data to be manually entered and calculated from the Revit model. Therefore, even the process of automating a part of the subset, can reduce the time it takes to generate results, whilst reducing user input errors. If the requirements are met, and the method is validated, the data transfer can also contribute to the accuracy of the calculation results.

ACKNOWLEDGMENTS

The authors would like to acknowledge the predicate for this article, which was developed by the students of Building Informatics at Aalborg University, and the authors would like to thank the contributors for their input.

REFERENCES

Andriamamonjy, A., Saelens, D., & Klein, R. (2018). An automated IFC-based workflow for building energy performance simulation with Modelica. *Automation in Construction*, *91*, 166–181. https://doi.org/10.1016/j.autcon.2018.03.019

Bazjanac, V. (2008). IFC BIM-Based Methodology for Semi-Automated Building Energy Performance Simulation. *CIB-W78 25th International Conference on Information Technology in Construction, Santiago, Chile, July 15-17, 2008*. Retrieved from https://digital.library.unt.edu/ark:/67531/metadc897563/

Borrmann, A., König, M., Koch, C., & Beetz, J. (Eds.). (2018). *Building Information Modeling*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-92862-3

Bryman, A., & Bell, E. (2011). *Business research methods*. Oxford University Press. Retrieved from https://books.google.dk/books?id=YnCcAQAAQBAJ&printsec=frontcover&dq=isbn:9780199583409&hl=en&as_brr=3&cd=1&source=gbs_api#v=onepage&q&f=false

Building SMART. (2018). Coordination View Version 2.0 Summary — Welcome to buildingSMART-Tech.org. Retrieved May 9, 2019, from http://www.buildingsmart-tech.org/specifications/ifc-view-definition/coordination-view-v2.0

CIC. (2013). Building Information Model (Bim) Protocol. *Construction Industry Council*, 15.

Eastman, C. (2016). *BIM Handbook BIM Handbook Rafael Sacks*.

Gram-, K. (2010). 11 . Housing in a sustainable consumption perspective, 178–191. https://doi.org/https://doi.org/10.4337/9781783471270.00021

Habibi, S. (2017). The promise of BIM for improving building performance. *Energy and Buildings*, *153*, 525–548. https://doi.org/10.1016/j.enbuild.2017.08.009

Harrestrup, M., & Svendsen, S. (2015). Changes in heat load profile of typical Danish multi-storey buildings when energy-renovated and supplied with low-temperature district heating. *International Journal of Sustainable Energy*, *34*(3–4), 232–247. https://doi.org/10.1080/14786451.2013.848863

Home | dRofus. (2019). Retrieved April 24, 2019, from https://www.drofus.no/en/

ISO. (2018). ISO 16739-1:2018 Preview Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries -- Part 1: Data schema. Retrieved April 15, 2019, from https://www.iso.org/standard/70303.html

Kamel, E., & Memari, A. M. (2019, January). Review of BIM's application in energy simulation: Tools, issues, and solutions. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2018.11.008

Kassem, M., Kelly, G., Dawood, N., Serginson, M., & Lockley, S. (2015). BIM in facilities management applications: A case study of a large university complex. *Built Environment Project and Asset Management*, *5*(3), 261–277. https://doi.org/10.1108/BEPAM-02-2014-0011

Pinheiro, S., Wimmer, R., O'Donnell, J., Muhic, S., Bazjanac, V., Maile, T., … van Treeck, C. (2018). MVD based information exchange between BIM and building energy performance simulation. *Automation in Construction*, *90*, 91–103. https://doi.org/10.1016/j.autcon.2018.02.009

REBUS. (2015). REBUS - REnovating BUildings Sustainably, 1–133. Retrieved from http://rebus.nu/

What is Dynamo? | The Dynamo Primer. (2018). Retrieved May 8, 2019, from https://primer.dynamobim.org/01_Introduction/1-2_what_is_dynamo.html

Wix, J., & Karlshøj, J. (2010). Information Delivery Manual Guide to Components and Development Methods. *BuildingSMART*, 84. Retrieved from http://idm.buildingsmart.comhttp//idm.buildingsmart.comashttp://idm.buildingsmart.com

BIM: FM for Healthcare: Lost in Transition

Julie Comlay[1*], Ricardo Codinhoto[1], Kemi Adeyeye[1]
[1]Architecture and Civil Engineering, University of Bath, Claverton Down, UK
*email: J.Comlay@bath.ac.uk

Abstract

The context of delivery for in-house facilities management (FM) is one of insufficient resources, namely financial, people and time, to develop strategic solutions that improve FM service delivery models; whilst managing a complex data landscape of hybrid digital and analogue data. Digitalisation of the FM model with automated data capture, productive workflows and integrated data systems is a viable alternative to current FM delivery models. A systematic literature review and comparative thematic analysis of BIM implementation for facility management was used to identify progress, stagnation and new research directions. The results indicate a research gap where delivery of a methodology for BIM: FM implementation based on building typologies i.e. education, public, healthcare etc. is required to evolve the BIM paradigm and engage with BIM for FM. Currently, BIM for FM implementation relies on individual organisations to move the model forward without support for a complex data information modelling solution.

Keywords: Building Information management, Facility management, Healthcare, digitalisation, Information Modelling.

1. Introduction

Facilities management teams ensure maintenance of the physical infrastructure, deliver operational space and reduce health and safety risks for users, to achieve organisational aims. For organisations with large estates, another aspect of the role is the management of energy consumption and reducing energy usage to deliver sustainable solutions. Automated data capture, energy consumption and integration of the building management system (BMS) data with FM data and a BIM model makes data available for analytics which would then allow decision-making about energy issues with strategic solutions, to be based on historic data. Facility management is a data intensive service, liaising with specialist contractors and internal technicians to deliver a built environment that meets organisational needs and complies with relevant statutory and regulatory requirements including sustainability targets.

The potential for BIM: FM is a virtual 3D model with attached data that synchronises using bi-directional data flow between FM specialist software and BIM, this is known as a digital twin of the physical building (Ismagilova et al., 2019). The digital twin for FM is a 3D model that mirrors the physical model where proposed changes to the built fabric of a building may be analysed and used for solution testing before procurement, and for remodelling and problem solutions. This 3D digital model identifies asset location and the complex data held on assets, warranties, manufacturer, model delivers accessible data. Data can be automatically collected and communicated using devices known as the 'Internet of Things' (IoT); which together with the digital twin links data streams and has the potential to automatically schedule maintenance activities. This would release technicians from mundane tasks such as meter readings, which can be easily achieved through the application of technology and ensuring the use of technical specialists to deliver innovative and creative solutions, not suited to machine learning or artificial intelligence.

The low adoption rates for BIM: FM implementation are due to the complexity of the BIM paradigm, a lack of BIM & FM expertise among construction professionals and a decided lack of support in the form of guidance and standards (Bosch et al., 2015; Ilter et al., 2015; Love et al., 2014; Pärn et al., 2017; Tan et al., 2018). UK BIM for design and construction stages are delivered through a national strategy using British Standards, PAS 1192 1-6 series, guidance documents and support organisations in the UK. January 2019, the UK has published new international BIM standards BS EN ISO19650-0:2019 (Transition guidance on BS EN ISO19650); BS EN ISO 19650-1:2019 (Concepts and principles) & BS EN ISO 19650-2:2019 (Delivery phase of Assets), with chapters for specific countries. These new BS EN ISO's replace BS1192:2007 and PAS1192-2 in the UK suite of BIM documentation; PAS1192-3, 4, 5 & 6 remain valid until 2020 (cdbb, 2019). The concurrent development of a national standard and guidance enabling BIM information management for BIM: FM for existing estate, which integrates BS EN ISO 19650:2019 series and ISO 41001:2018, has not yet been realised, leaving BIM: FM waiting for support, they are lost in transition between their many hybrid systems to a BIM: FM solution.

At the same time the USA implemented a different strategy for BIM implementation without the use of standards, based on a model of commercial market stimulus. Singapore has used a hybrid solution for standards as a city nation, with required submission for planning as BIM models and the use of AIM models for OPEX activities. Implementation solutions for data integration between BIM: FM and FM software, bi-directional data flows and the level of data granularity are essential to maximise the benefits of BIM: FM implementation (Becerik-gerber et al., 2012; Carbonari et al., 2018; Patacas et al., 2016; Sacks et al., 2018). Overall, this represents the interoperability needs for a BIM: FM methodology and BIM implementation will resolve the existing inefficiencies of siloed data, isolated data and keeping data up to date. Currently, in the UK there is not a proposed strategic solution to integrate BIM: FM which has new buildings coming on stream and existing estate, within the BIM paradigm. FM professionals do not have the expertise, time, financial or support from the UK government in the form of standards & guidance to deliver the complexity that is BIM: FM.

This systematic review considers the status of BIM for facility management implementation for existing and new buildings in research based on articles between 2014 and 2018 (inclusive). Comparative thematic analysis relates the themes from the reviewed articles to themes identified in Volk, Stengel & Schultmann, (2014) article, which has a very high citation rate. The next section describes the methodology and how articles were selected and excluded using Systematic Literature

Review Specification Protocol (SLRSP) detailed in Table 1, followed by results and discussion that report the bibliometric assessment of articles and thematic comparative analysis of articles selected for review.

2. Material and methods

This systematic review is an evaluation of the status of BIM: FM implementation from 2014-2018; it offers a transparent, accessible overview that is rigorous, with a transparent methodology and the research is reproducible (Denyer et al., 2009). The occurrence of bias is reduced using a systematic review when compared to other types of review and the use of a checklist delivers transparency (Petticrew et al., 2006).

Table 1: Systematic Literature Review Specification Protocol (SLRSP)
(adapted from Schardt et al. (2007))

Criteria for Inclusion of Articles in the review	
Study population/participants and conditions of interest	Facility management teams, population is worldwide
Interventions	Papers about BIM implementation within FM departments between 2014 – 2018
Comparisons	Thematic comparative analysis with an article by Volk et al. (2014)
Outcomes of interest	Similarities and differences of outcomes
Setting	Organisations with existing estate, hospitals
Study method	Any method
Language	Written in English
Criteria for Exclusion of articles in the review	
References	Dated
Technology	Very specific about technology for BIM
Software	Specific about file types
Conference Papers	Excluded for reasons of uncertain reliability
Publication	Date range 2014 – 2018 inclusive
Search Methods	
Electronic Databases	Web of Science, Scopus, Science Direct
Other search methods	Checking references in papers, and snowballing.
Methods of Review	
Reviewers	One reviewer of journals, primary author.
Quality assessment	Based on checklist derived from social science research and medical research, critical appraisal skills programme (CASP)
Data Extraction	Excel spreadsheets to track papers and status based on the specification protocol. One reviewer (author) to action.
Narrative Synthesis	Carried out using the framework below: Bibliometric Analysis: 1. Geographical location of authors 2. Articles over time 3. Article distribution in Journals 4. Method uses 5. Methodological use 6. Research themes Thematic Analysis: 1. Thematic analysis of selected journal papers 2. Develop a preliminary synthesis of findings 3. Explore methods, findings, outcomes and relationships 4. Compare and contrast selected articles with themes identified in Volk et al. (2014).

The papers selected and reviewed are published journals with a peer review system about BIM: FM implementation for BIM: FM legacy estate. The specification protocol for inclusion of papers in the review is based on PICOS (Population, Intervention, Comparison, Outcome, Setting and study method) and detailed in the specification protocol as shown in Table 1.

The search terms and Boolean operators used include BIM, Building Information Model*, facilit* management. The breakdown of the papers collected is detailed in Figure 1, and exclusion and inclusion criteria applied using the Systematic Literature Review Specification Protocol (SLRSP) in Table 1. Initially 942 articles were identified, a total of 876 articles were excluded. The analytical stage reviewed 31 journal articles using the SLRSP shown in Table 1.

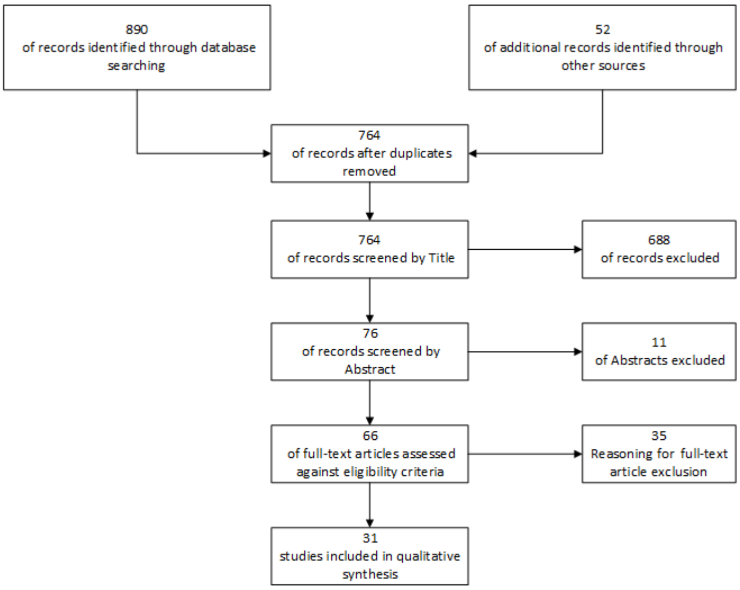


Figure 1: PRISMA Flow Diagram of Process for Systematic Review
(adapted from Moher et al. (2009))

3. Results and discussion

3.1 Bibliometric Analysis

Qualitative research is increasing the use of bibliometric analysis as an evaluation tool for research (Ellegaard et al., 2015). Bibliometric analysis evaluates the robustness of the research articles under review and the results can be used as a basis for a decision-making tool for organisations, funding bodies, future research applications as the analysis considers the relevance of the research to targets and goals (Ellegaard et al., 2015). Bibliometric analysis also supports the identification of incremental knowledge in areas where the production of academic articles where the production of academic articles is fast. The authors contributing to BIM: FM implementation research are based in twenty countries, as detailed in **Error! Reference source not found.**, with the leading number of authors based in Higher Education facilities in world regions of Europe, Asia, Australasia (Australia & New Zealand), North America (USA & Canada) and Africa.

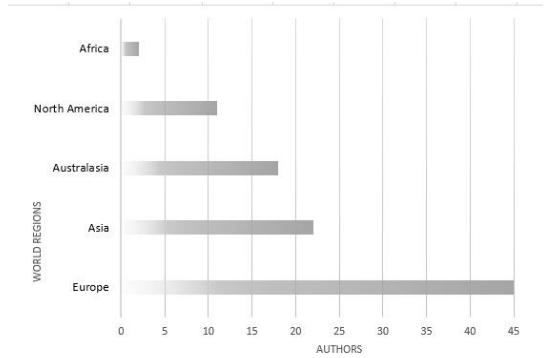


Figure 2: World regional distribution of research authors

The years with increased authors (above 15) for BIM implementation in FM, worldwide were 2015 and 2018, shown in **Error! Reference source not found.**. Authors based in Europe were 94% in 2015 which reduced to 41% based on the substantial increase overall, in articles published in journals in 2018. There was a significant increase in authors by 51% in 2018 with the European region authors contributing 44% between 2014 and 2018 inclusive as detailed in **Error! Reference source not found.**.

There are a range of external factors which are relevant to the increase in articles for BIM: FM implementation which include requirement to publish for a PhD, the research BIM for design and construction stages are saturated and BIM: FM is increasing in academic interest. The increase in articles is positive for raising the profile of BIM: FM implementation, however, low rates of BIM: FM implementation for existing buildings suggests practitioners are not sufficiently confident (NBS, 2018). An additional factor is that the research lacks sufficient detail regarding BIM: FM implementation methodologies for implementation for particular building typologies (Pishdad-Bozorgi et al., 2018).

Table 2: Authors location by papers submitted over time

		2014	2015	2016	2017	2018	Count per Region
Africa	South Africa					2	2
North America	Canada			1			1
	USA		1	4		4	9
Australasia	Australia	5			7	6	18
	New Zealand			1			1
Asia	Iran			1			1
	Malaysia			1		1	2
	Hong Kong				1	6	7
	Singapore				1		1
	South Korea					6	6
	Taiwan					5	5
	Turkey		2				2
Europe	Belgium			1			1
	UAE			1			1
	Italy				3		3
	Finland		3			5	8
	Portugal			2			2
	Netherlands		3				3
	Switzerland		1				1
	UK		7		2	16	25
	Count Total by year	5	17	12	14	51	99

Journal publication over time as detailed in **Error! Reference source not found.** demonstrates that Automation in Construction has published 7 articles between 2014 and 2018; Facilities published three articles and Built Environment Project and Asset Management, Engineering Construction and Architectural Management, International Journal of Building Pathology and Adaptation all published two articles each, over the time period. This demonstrates a wide selection of publications available for journal publication.

Considering the methods chosen to investigate the area of interest, the use of literature review is the initial approach in 2014, method choices then include case study and the use of mixed methods as a combination of interview, observation, secondary data and survey as detailed in **Error! Reference source not found.**. The method for the research profile changed in 2017 when mixed methods and case study increase by 50% when compared to the use of literature review in 2018.

Table 3: Distribution of articles published in Journals over Time

JOURNALS	2014	2015	2016	2017	2018	Total
Advanced Engineering Informatics					1	1
Automation in Construction	1			1	5	7
Buildings		1				1
Built Environment Project & Asset Management		2				2
Civil Engineering Journal			1			1
Construction Management & Economics		1				1
Engineering Construction and Architectural Management				1	1	2
Facilities			1	1	1	3
Innovative Infrastructure Solutions				1		1
International Journal of Built Environment			1			1
International Journal of Building Pathology and Adaptation					2	2
International Journal of Sustainable Built Environment				1		1
Journal for Facility Management		1				1
Journal of Building Engineering					1	1
Journal of Corporate Real Estate					1	1
Journal of Facilities Management					1	1
Journal of Management in Engineering					1	1
Renewable and Sustainable Energy Review		1				1
Structural Survey		1	1			2
Total	1	7	4	5	14	31

Mixed methods and Case Study reduce by 66% in 2016 and stays at that level for 2017, after a peak in 2015. However, from 2018 the increase in use is significant. It should also be noted that a significant number of articles reviewed do not state sufficient detail for the research to be repeatable.

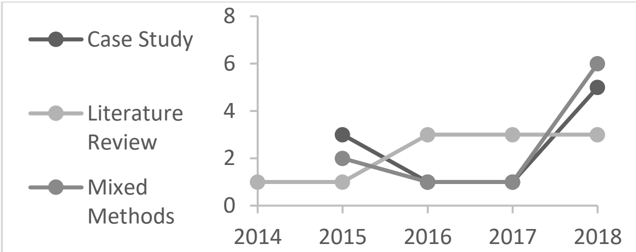


Figure 3: Methods chosen for articles

This review identifies eight case studies that are building typologies studied, limited to 5 universities, 2 Civic buildings and an office building. There are insufficient case studies to be able to draw conclusions that may be generalised across any of the typologies presented. Similarly, due to the low numbers i.e. under 100, the cumulative results of the research are not generalisable, however, all contribute to knowledge.

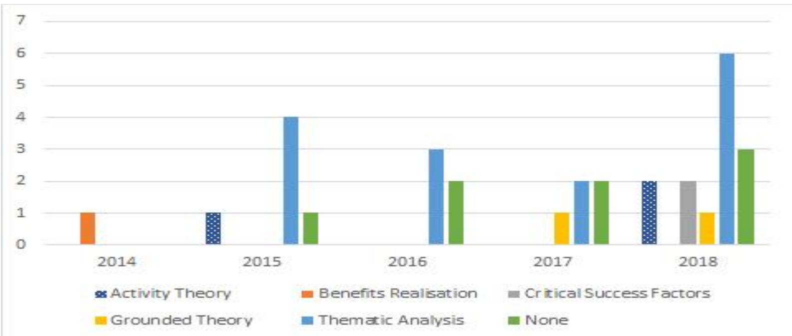


Figure 4: Methodological Models

The analysis used in this review is thematic and the articles under review were classified into three themes, as in **Error! Reference source not found.**, BIM: FM Challenges and Opportunities; BIM: FM Integration and BIM: FM Status. The research themes in 2014 and 2015 concerned BIM: FM integration and BIM: FM status. BIM: FM challenges and opportunities was introduced as a theme from 2016 onwards, in 2018 BIM: FM integration is the dominant theme.

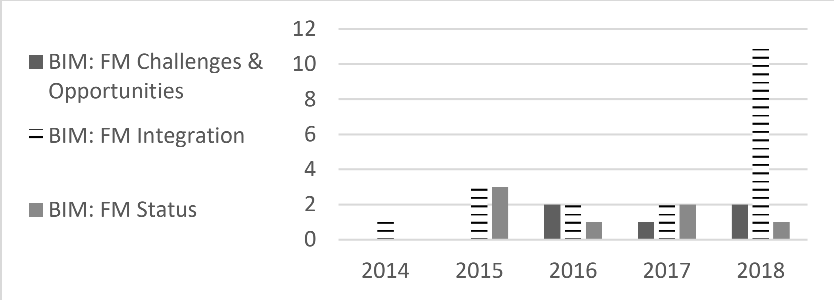


Figure 5: Classification of research Themes

2.2 Thematic Analysis of selected Journal Papers

The over-arching themes from the critical analysis of the articles when compared to Volk et al. (2014) are 1) BIM FM Challenges and Benefits, 2) Data Model Integration, 3) Expertise in BIM & Facilities Management and 4) Major Levers for BIM FM implementation. Two categories from Volk et al. (2014), which have not been addressed are 'data analytics' and 'capability & maturity assessment system'. Additional themes from the reviewed articles include 'FM collaboration with design & construction' and 'Api's and Plug-ins' identified by researchers after Volk et al. (2014) as shown in **Error! Reference source not found.**. These outcomes demonstrate that the review by Volk et al. (2014) was comprehensive at the time of publication and continues to align with research in this subject area today.

Table 4 Themes Unidentified by Volk et al. (2014)

New research themes *Unidentified* in Volk et al. (2018)	2014	2015	2016	2017	2018	Total Themes 2014-2018
FM collaboration with design & construction		1	1	1	3	6
Api's & Plug-ins		2		1		3
Sub-total of themes categories per year	0	3	1	2	3	9

Pishdad-Bozorgi et al. (2018) identified that data transfer from an FM enabled BIM model can directly import into computerised aided facilities management system (CAFM) software with no data loss or atrophy using the capabilities of interoperable software export i.e. COBie. However, there are four current version types of IfC and COBieLite which suggests that planning, testing and specifying data to a granular level is required to achieve successful delivery of data for an FM organisation with legacy software systems. The absolute clarity that is required regarding data when transferring between different software is a critical aspect of successful BIM: FM implementation methodology, as demonstrated by the interest in research undertaken about data integration for 2018 as in Figure 6. The most likely methodology will include web based middleware software solutions to achieve reliability, deliver bi-directional data synchronisation and automated validation and verification using the cloud (Ilter et al., 2015; Kensek, 2015; Pärn et al., 2017).

Considering the question of research interest in BIM: FM implementation for existing building indicates that the challenges for BIM: FM implementation are still as relevant and significant in 2018 as in 2013. Referring to **Error! Reference source not found.** the emphasis has changed within the research themes identified, 2016 & 2018 demonstrate reduction in research from BIM: FM Challenges and Opportunities and peaked at 20% in 2017. Data model integration reduced from 2015 to 2017 but sees a significant swing of from -28% from 2017 and in 2018 reaching a level of over 20%. Expertise in BIM and FM research is -10% in 2015 which showed a small increase in 2016 with levels dropping in 2017. Major levers for BIM: FM implementation peaked in 2016 with reducing levels in 2017 & 2018. IT is significant that in 2016 there was 20% research activity and 2018 achieved 45% in 2018.

It is unclear what the exact stimulus for the increase in 2018, external influencing factors that are relevant include the potential saturation regarding research into BIM for design and construction, with

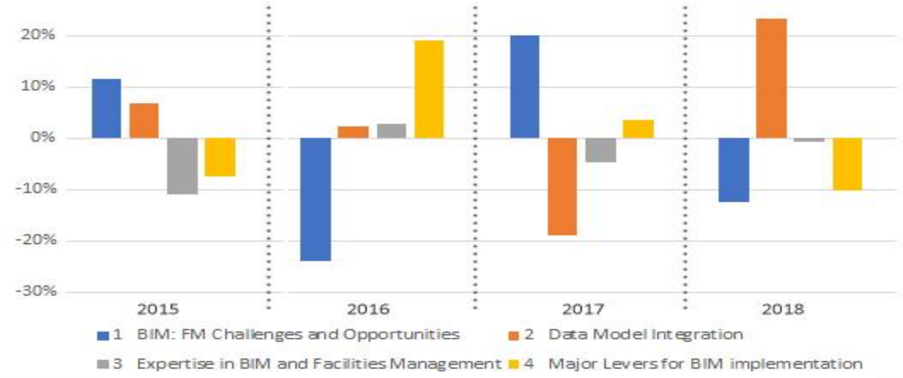


Figure 6 Year-on year Thematic Distribution Percentage

BIM: FM implementation is the next logical research topic in the field. Additionally the increase in research in the UK could be due to the UK Government Soft Landing requirement for asset management in government funded procurement (Cabinet Office, 2013). Subsequent NBS national BIM reports demonstrate that BIM: FM implementation is slow to progress in the UK based on requests for COBie data at completion and has remained static in 2018/2019 (NBS, 2019).

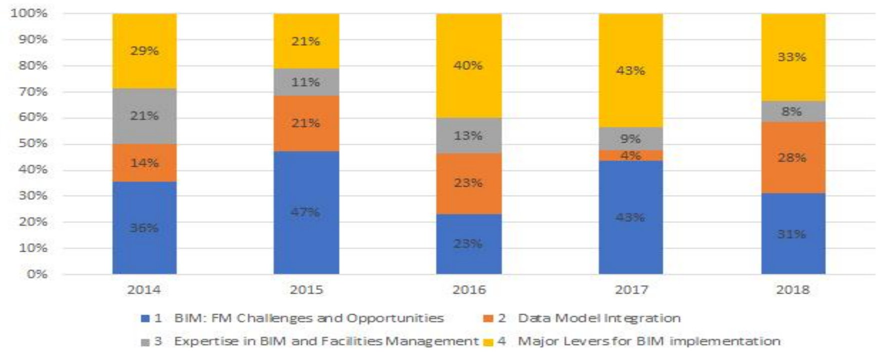


Figure 7 Distribution of Themes Comparative Analysis with Volk et al. (2014)

The themes in the articles as identified in **Error! Reference source not found.** can be further sub-divided to identify the priority themes. These are BIM: FM benefits, the Value of BIM for organisations and the adaptations required to achieve BIM: FM. FM data needs and FM engagement with BIM are a priority together with interoperability and lifecycle. Each of the themes receives similar research emphasis in 2018, however, expertise in BIM and FM management is less than 10% of activity.

Due to the lack of reported longitudinal case studies with regard to BIM: FM implementation, there are few cases of adoption that reach the attention of the FM community as identified by (Pishdad-Bozorgi et al., 2018). The Sydney Opera House, Sutter Health and Manchester Town Hall studies have some valuable insights. However, these are examples based on different continents with different national approaches to BIM standards and guidance for implementation; there are also typology differences of a concert hall, private healthcare and an historic building which make findings difficult to generalise.

4. Conclusion

This study set out to determine the ‘state of the art’ in research about BIM: FM implementation for healthcare between 2014 and 2018 inclusive. The systematic research process identified there were no articles in journals regarding this topic area. This is a significant finding considering the importance of healthcare buildings to society and the complexity of maintaining such building complexes. As a result, the research focus widened to the implementation of BIM: FM for existing buildings.

Comparative analysis of the selected articles against themes from Volk et al. (2014), was undertaken. The findings show that BIM: FM has seen a 45% increase in the number of articles using the themes identified for Volk et al. (2014) between 2014-2018, with over 50% published in 2018. These findings suggest that research into BIM: FM implementation is now a primary research topic, although research into BIM: FM for existing buildings is limited.

Facility management teams understand, in the abstract, that BIM: FM for their organisation would deliver significant long-term benefits but have little or no knowledge how to take it forward, as most of the BIM knowledge sits within design and construction. Currently there is no strategy for education of the workforce in BIM: FM to aid transition to BIM solutions for FM. ISO 19650-2; 2019 delivers no advancement on a methodology for BIM: FM implementation for existing building, therefore, future research into BIM: FM standards and demonstration of the 'Value' of BIM for FM to facilitate funding from management, are an essential step together with decoding what types of data are required to deliver Facility Management, noting the distinction between data required for different building typologies (Love et al., 2014; Carbonari et al., 2015; Barbosa et al., 2016; Hosseini et al., 2018; Lu et al., 2018; Pishdad-Bozorgi et al., 2018).

This paper also identifies a gap in the body of literature where a methodology for implementation of BIM: FM for new and existing buildings across building typologies, is required. Additionally, those researching this area should make their contributions more robust by including sufficient detail regarding the method and methodology used to undertake the research to improve the rigour and repeatability of the research. The systematic literature review protocols used in this paper contribute to this gap as a way forward to deliver repeatability for research in construction. The systematic review contributes to the understanding of the status of BIM: FM implementation at this time; which can be likened to being in a waiting room, anticipating a move to a digitalised platform and the whistle has not blown to set everyone off. BIM for FM is most definitely lost in transition.

References

Barbosa, M. J., Pauwels, P., Ferreira, V., & Mateus, L. (2016). Towards increased BIM usage for existing building interventions. *Structural Survey*, *34*(2), 168-190. doi:10.1108/ss-01-2015-0002

Becerik-gerber, B., Jazizadeh, F., Li, N., & Calis, G. (2012). Application Areas and Data Requirements for BIM- Enabled Facilities Management. *Journal of Construction Engineering and Management*, *138*(3), 431-442. doi:10.1061/(ASCE)CO.1943-7862.0000433

Bosch, A., E.D. Love, J. M., Steve, P., Volker, L., & Koutamanis, A. (2015). BIM in the operations stage: bottlenecks and implications for owners. *Built Environment Project and Asset Management*, *5*(3), 331-343. doi:10.1108/bepam-03-2014-0017

Cabinet Office. (2013). *Government Soft Landings,*. UK Retrieved from http://www.bimtaskgroup.org/reports.

Carbonari, G., Stravoravdis, S., & Gausden, C. (2015). Building information model implementation for existing buildings for facilities management: a framework and two case studies. *1*, 395-406. doi:10.2495/bim150331

Carbonari, G., Stravoravdis, S., & Gausden, C. (2018). Improving FM task efficiency through BIM: a proposal for BIM implementation. *Journal of Corporate Real Estate, 20*(1), 4-15. doi:10.1108/JCRE-01-2017-0001

cdbb. (2019). ISO 19650 Transition Update - Question and Answers. Retrieved from https://bim-level2.org/globalassets/pdfs/new-iso19650_uk_transition_questions_answers_latestupdated_11_dec_2018.pdf

Denyer, D., & Tranfield, D. (2009). Producing a Systematic Review. In D. A. Buchanan & A. Bryman (Eds.), *The Sage Hanbook of Organisational Research Methods* (pp. 671-689). London: Sage.

Ellegaard, O., & Wallin, J. (2015). The bibliometric analysis of scholarly production: How great is the impact? *Scientometrics, 105*(3), 1809-1831. doi:10.1007/s11192-015-1645-z

Hosseini, M., Roelvink, R., Papadonikolaki, E., Edwards, D., & Pärn, E. (2018). Integrating BIM into facility management. *International Journal of Building Pathology and Adaptation, 36*(1), 2-14. doi:10.1108/IJBPA-08-2017-0034

Ilter, D., & Ergen, E. (2015). BIM for building refurbishment and maintenance: current status and research directions. *Structural Survey, 33*(3), 228-256.

Ismagilova, E., Hughes, L., Dwivedi, Y. K., & Raman, K. R. (2019). Smart cities: Advances in research—An information systems perspective. *International Journal of Information Management, 47*, 88-100. doi:10.1016/j.ijinfomgt.2019.01.004

Kensek, K. (2015). BIM Guidelines Inform Facilities Management Databases: A Case Study over Time. *Buildings, 5*(3), 899-916. doi:10.3390/buildings5030899

Love, P. E. D., Matthews, J., Simpson, I., Hill, A., & Olatunji, O. A. (2014). A benefits realization management building information modeling framework for asset owners. *Automation in Construction, 37*, 1-10. doi:10.1016/j.autcon.2013.09.007

Lu, Q., Chen, L., Lee, S., & Zhao, X. (2018). Activity theory-based analysis of BIM implementation in building O & M and first response. *Automation in Construction, 85*, 317-332. doi:10.1016/j.autcon.2017.10.017

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & The, P. G. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLOS Medicine, 6*(7), e1000097. doi:10.1371/journal.pmed.1000097

NBS. (2018). NBS National BIM Report 2018. Retrieved from https://www.thenbs.com/knowledge/the-national-bim-report-2018

NBS. (2019). NBS National BIM Report 2019. Retrieved from https://www.thenbs.com/knowledge/national-bim-report-2019

Pärn, E. A., Edwards, D. J., & Sing, M. C. P. (2017). The building information modelling trajectory in facilities management: A review. *Automation in Construction, 75*, 45-55. doi:10.1016/j.autcon.2016.12.003

Patacas, J., Dawood, N., Greenwod, D., & Kassem, M. (2016). Supporting building owners and facility managers in the validation and visualisation of asset information models (AIM) through open standards and open technologies. *Journal of Information Technology in Construction (ITcon), Special issue: CIB W78 2015 Special track on Compliance Checking,, 21*, 434-455.

Petticrew, M., & Roberts, H. (2006). *Systematic Reviews in the Social Sciences: A Practical Guide*. Oxford: Blackwell.

Pishdad-Bozorgi, P., Gao, X., Eastman, C., & Self, A. P. (2018). Planning and developing facility management-enabled building information model (FM-enabled BIM). *Automation in Construction, 87*, 22-38. doi:10.1016/j.autcon.2017.12.004

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *BIM Handbook: A Guide to Building Information Modeling For Owners, Designers, Engineers, Contractors and Facility Managers* (Third ed.). Hoboken, New Jersey, USA and Canada.: John Wiley & Sons, Inc.

Schardt, C., Adams, M. B., Owens, T., Keitz, S., & Fontelo, P. (2007). Utilization of the PICO framework to improve searching PubMed for clinical questions. *BMC Medical Informatics and Decision Making, 7*, 16-16. doi:10.1186/1472-6947-7-16

Tan, A. X. T., Zaman, A., & Sutrisna, M. (2018). Enabling an effective knowledge and information flow between the phases of building construction and facilities management. *Facilities, 36*(3/4), 151-170. doi:10.1108/F-03-2016-0028

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction, 38*, 109-127. doi:10.1016/j.autcon.2013.10.023

Developing a BIM based asset management strategy – first highlights from specific client case study

Mustapha Munir[1*], Pedro Mêda[2] and Hipólito Sousa[3]

[1]School of Architecture, University of Liverpool
[2]Construction Institute, CONSTRUCT – Gequaltec, Faculty of Engineering University of Porto
[3]CONSTRUCT – Gequaltec, Faculty of Engineering University of Porto
[*]email: mmunir@liverpool.ac.uk

Abstract

Asset managers require meaningful asset data in order to effectively manage their assets. Asset owners from the public and private sectors are increasingly adopting Building Information Modelling (BIM) in the lifecycle of their investments in order to improve asset data delivery, operations and maintenance practices. Despite this momentum, there is insufficient understanding by asset owners of the right standards, processes and policies to follow in delivering such data. Therefore, further awareness and research are needed to develop good BIM implementation practices in the Architecture, Engineering, Construction, Owner and Operator (AECOO) industry in order to improve the adoption of BIM-based processes by asset owners. The paper seeks to understand the current Asset Management (AM) methods and further aims to develop a BIM-based AM strategy that focuses on the development of a consolidated Asset Information Model (AIM) that can support building information management with the optional requirement of 3D-models in a specific client case study. The case study is a public asset owner that manages residential buildings and social housing. The purpose of the paper is to frame, evaluate and test the defined strategic approach based on organisational requirements and established AM development stages. The first stage which is covered by this paper involves the development of a BIM-based AM strategy that is based on non-graphical data and documentation. The research, methodology and outcomes led to the following results: (a) developing better understanding by the asset owner and improved awareness of the difficulties of implementing the defined BIM-based AM strategy in a practical case study; (b) identifying generic barriers and obstacles relating to the implementation of a BIM-based approach in managing asset data of all building stock owned by the public asset owner; (c) highlighting direct uses of the strategy and benefits towards future asset operation and maintenance actions; (d) demonstrating the business value of BIM across building maintenance actions and new construction processes.

Keywords: Data, information, COBie, Asset Operations, client requirements

1. Introduction

Building Information Modelling (BIM) represents the consistent and continuous use of digital information across the entire lifecycle of a built asset, including its design, construction and operation (Borrmann, König, Koch & Beetz, 2018). Comparative market analysis studies (Kassem & Succar, 2017) evidence that BIM adoption ranges from country to country, with each having distinct strategies. BIM adoption is now a common feature of the Architecture, Engineering, Construction, Owner and Operator (AECOO) industry in many countries around the world. This methodology is aimed at accelerating the pace of the AECOO industry towards new levels of efficiency, sustainability and productivity. Despite the misunderstandings around BIM (Hjelseth, 2017), stakeholders in the AECOO industry are interested in deriving BIM benefits from all phases of asset development, even though they lack extensive knowledge of process-based requirements and implications (Grussing, 2013). There have been more studies on the benefits of BIM during the design and construction phases, with few focusing on its implementation and potential benefits in asset operations and maintenance (Love et al., 2014). Furthermore, little research interest has been evidenced in investigating the uses of BIM in post-handover project processes and in developing BIM adoption strategies for existing buildings (Eastman, Teicholz, Sacks & Liston, 2011; Carbonari, Stravoravdis & Gausden, 2015). A growing perception of BIM amongst stakeholders in the AECOO industry is that BIM facilitates Knowledge Management (KM) activities including acquisition, extraction, storage, sharing and updating of building information in a structured way right through an asset's lifecycle (Deshpande et al., 2014). This becomes interesting when data from the building information model may help to prevent information or knowledge breaks during major refurbishments or as a result of change of ownership of the built asset (Borrmann et al., 2018).

This research is developed from the asset manager or asset owner perspective and is aimed at focusing on the benefits and challenges of implementing BIM in Asset Management (AM). This study views BIM from the perspective of Building Information Management (Parsanezhad & Dimyadi, 2014). Furthermore, the scope of this study focuses on the implementation of BIM for existing buildings. In this context, the development of a BIM-based AM strategy for built assets that have been in service for several decades and will continue to be in use for many years with major, minor or even no interventions carried out. This is necessary because maintenance actions and operation costs can be three times higher than construction costs and five to seven times higher than the initial investment costs (Grussing, 2013; Korpela, Miettinen, Salmikivi, & Ihalainen, 2015). On this premise, the outcomes of this study can contribute to effective asset maintenance and management strategies, thereby leading to the reduction of the global asset operation costs in the long-run. The contributions can be even more relevant when carrying out asset intervention actions where it is possible to leverage on the data provided by the building information models in decision-making regarding the best design solutions and products that have proven durability and savings as well as environmental and energy efficiency targets and performance.

The paper seeks to understand the current AM methods in a specific client case study. Also, the paper aims to develop a BIM-based AM strategy that focuses on the development of a consolidated Asset Information Model (AIM) that can support building information management with the optional requirement of 3D-models. The case study is a public asset owner that manages residential buildings and social housing. The purpose of the paper is to frame, evaluate and test the defined strategic approach based on organisational requirements and established AM development stages. The first stage which is covered by this paper involves the development of a BIM-based AM strategy that is based on non-graphical data and documentation.

2. Review

2.1 Building Information Management

Over the building life-cycle, the amount of graphics and data required varies from stage to stage (Carbonari et al., 2015). Figure 1 shows the schematic evolution of the growing relevance of information throughout the life-cycle of an asset.

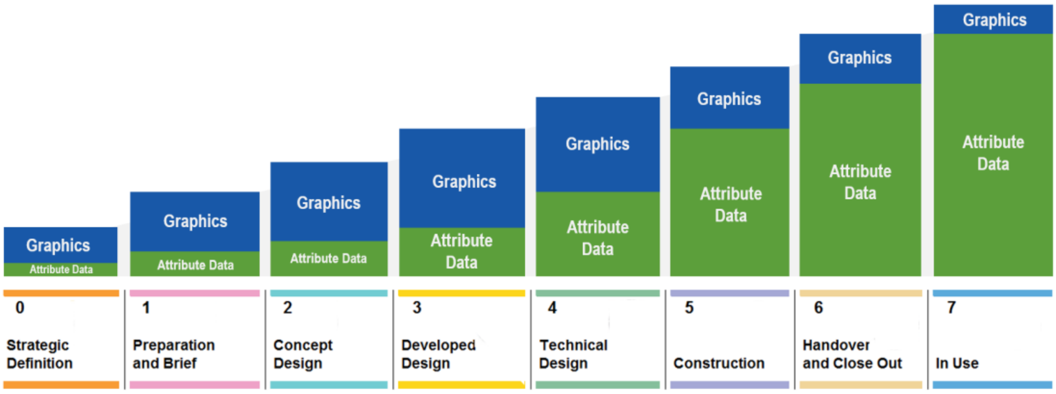


Figure 1: Graphics and Data evolution over construction life-cycle (adapted from Carbonari et al., 2015; PAS 1192-3 (BSI, 2014) and RIBA, 2013)

Despite this awareness, many studies have focused on developing strategies to deliver extensive graphical models for building operations (Volk, 2014). Similarly, 3D-geometric data is reported to have little value in AM tasks (Munir, Kiviniemi, & Jones, 2019). The same assume that asset owners have difficulty on following and understanding the effort of the work. This occurs mainly due to the cost of the process and due to the absence of direct added value of the deliverables/result (Kassem & Succar, 2017). Furthermore, the nature and type of a building would influence the process-based strategic definition for BIM-based processes in AM. For most asset owners, their main concerns are geared towards asset characterisation and information delivery. However, there are situations where the development of a detailed 3D graphical model may be useful, for instance, the case of Heritage buildings. The recent events at Notre-Dame highlight the utility of a graphical model. Notwithstanding, the availability of graphical information can be an accessory at the initial stage or it can be produced in subsequent asset development phases in line with the main strategic requirement of the asset owner, which is to improve the knowledge and management capability for the built asset. The strategic approach in relation to the development of building information should be from the "Information to Graphic" perspective as opposed to the "Graphic to Information" order, by focusing on the identification of key datasets to create the (non-graphical part of the) AIM (Carbonari, et al. 2015).

There are AECOO industry standards such as Information Delivery Manuals (IDM), Industry Foundation Classes (IFC), Model View Definitions (MVD), buildingSMART Data Dictionary (bsDD) and BIM Collaboration Format (BCF) that have been developed for the creation, exchange and management of building information from design and construction stages to the operations and maintenance stage (Mêda, 2014; Cavka, Staub-French, & Poirier, 2017). Despite the development of several frameworks using one or more of these standards, IFC and Construction Operations Building Information Exchange (COBie) are the two main open source schemas that fulfil the exchange requirements for BIM-based information exchange in AM (Eastman et al., 2011). The AIM, despite using a common structure, can assume very distinct goals depending on the construction type, nature of ownership, and operations and maintenance strategy (Grussing, 2013).

2.2 Construction Operations Building Information Exchange (COBie)

The UK Government BIM strategy has led to the development of several guidelines and standards. Despite the efforts on technological standards, this approach is robust from the process viewpoint. Meaning that there is a strong concern in relation to the global achievements intended with BIM as well as balancing the different aspects of the implementation process (technology, processes and people) (Hjelseth & Mêda, 2016). In respect with the handover of construction information and utilisation of data in the operational stage of built assets, PAS 1192-3 (BSI, 2014a) and BS 1192-4 (BSI, 2014b) constitute the main guidelines. The first provides and overall vision of the lifecycle structure of BIM including specifications on the purpose of maintenance and the information requirements towards the implementation of Level 2 BIM of the UK strategy. On the other hand, BS 1192-4 (BSI, 2014b) or COBie provides further orientation on the information requirements by setting the framework for data exchange between applications and databases throughout the facility's lifecycle. Figure 2 presents COBie worksheets (blue, yellow, green, grey) that have been utilised in developing the BIM-based AM strategy in relation to the asset development phases. The tables highlighted in grey have been excluded from the strategy at this stage.

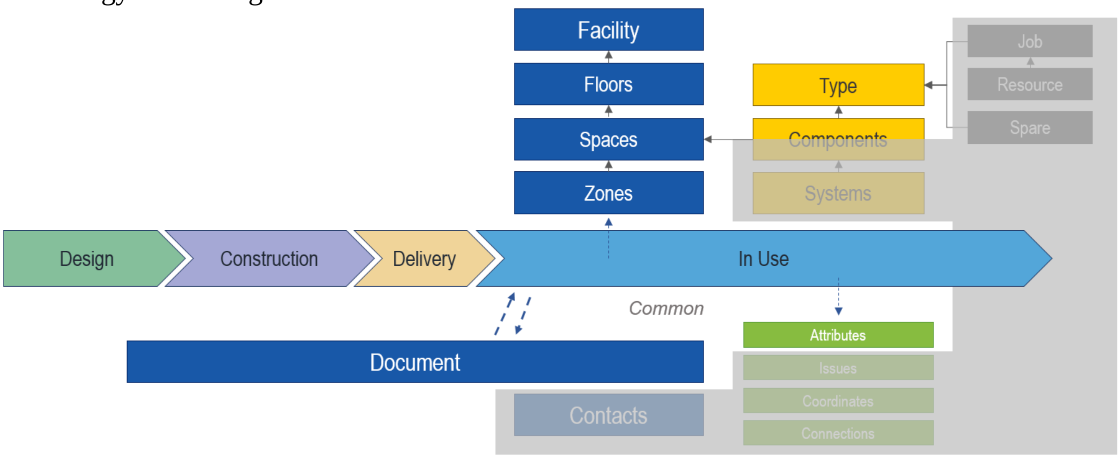


Figure 2: COBie tables utilised within the context of the developed study

2.3 Benefits and Barriers

A significant amount of existing buildings have more than one decade of service and many of them have more than one century. Considering the foregoing, it can be said that most of them do not belong to the "BIM era" as "traditional" approaches and formats such as CAD, .doc, .pdf documents, paper or a mix of both were utilised during asset development. Paper documents can range with several different contents to support the design and construction stages, depending on the moment they were produced. Even in situations where all the processes are structured and well supported, the information required for the development of the AIM is generally scattered, incomplete and inaccurate. Furthermore, the building can change ownership many times and this factor can lead to a total absence of project documentation or knowledge gaps. Notwithstanding, a streamlined definition and the organisation of essential and relevant datasets can facilitate the recreation of information that will produce a satisfactory AIM. This would enhance the asset manager's awareness on facility data and condition, thereby minimising knowledge gaps throughout the lifecycle. To make it possible, combined data analysis from documents with data capture from on-site inspections followed by data modelling are techniques that can be utilised to develop an AIM. In fact, site inspections can be very productive and worthy if the strategy integrates condition analysis of construction elements. Furthermore, in terms of business value and from a general perspective, the potential benefits of BIM are presented in Table 1 (Hossain, 2014):

Table 1: BIM for operation, maintenance and sustainability (Hossain, 2014)

Item	*Description*
Lifecycle analysis	Facility/asset management, monitoring, 3D visualisation, real time data access, maintenance schedule, auditing, emergency management
Retrofit	Retrofit decision making, repair and reconstruction
Energy	Building energy modelling, energy efficiencies and energy conservation
Safety	Safety facility management, hazard mitigation, fall prevention, fire prevention and disaster relief, integrated multidisciplinary model for security and safety management
Sustainability	Sustainable facility management, sustainable retrofit
Decommissioning	Analysing material composition prior to demolition

3. Methodology and Research Question

This paper is part of a study that aims to develop a BIM-based AM strategy in order to streamline the processes of a public asset owner that manages residential buildings and social housing. At this stage, the study is focused on the development of a consolidated AIM that can support building information management with the optional requirement of 3D models. This is due to the fact that all the projects were developed prior to BIM and most project documentation such as drawings only exist on paper. Furthermore, this study seeks to identify the asset owners' requirements and challenges in terms of documenting building information in order to develop and implement the strategy as well as the inherent business value to be derived from the whole process. Based on these assumptions, the following research questions are developed:

- What is the current state of information process management within the organisation?
- What are the strategic BIM-based information requirements of the asset owner?
- How would the new information requirements impact/influence/transform the processes presently in use by the public asset owner?
- What are the potential benefits of these processes?

3.1 Methodological Approach

To develop the study, several steps were identified in order to deliver the outcomes. As a result, two major tasks were developed at the initial stage. The first, investigated the organisation, its structure, main objectives, scope of action, building stock overview, processes and information systems. This task also included the objectives and requirements for the development of the BIM-based AM strategy. The second task identifies tools and methodologies that could fit the study purpose. Furthermore, it identifies information requirements, structures and expected outcomes through literature review. With the accomplishment of these tasks, it was possible to develop the BIM-based AM strategy and test its applicability on the selected case study. The case study is selected based on the following criteria:

i) Senior level management motivation to implement BIM within the organisation and across the building stock.
ii) The existence of change management programmes and recent investments aimed at optimising assets, enhancing maintenance actions and improving future developments as a result of documented building information from historical maintenance activities;
iii) The existence of project-level documentation such as "As-built" drawings, specifications and bill of quantities across the building stock;
iv) The existence of generic construction information across the building stock;
v) The existence of building information regarding all maintenance processes that have been carried out since handover across the building stock.

Figure 3 shows the methodological approach of this study:

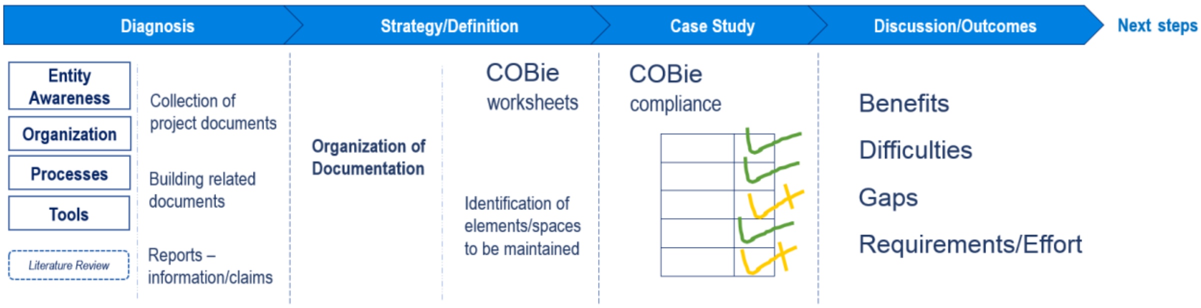


Figure 3: Methodological approach

The case study produced all the essential elements that were used in the development of the BIM-based AM strategy at the information and process level. It also enabled the forecasting of implications in terms of generalisations relating to the remaining building stock. This helped in terms of achieving the necessary information and definition of limits for incomplete data. The last aspect of the study led to a primary perception of the business value of BIM-based processes for the public asset owner at process and management level, as well as future developments.

4. Results: Case Study

4.1 Summary of the Case

An essential step was to understand and achieve a consistent understanding of the information and process level capability within the organisation. The public asset owner under study requested for anonymity but has authorised the use of all data and findings. These findings have been reported in accordance with research ethics and the confidentiality requirements of the public asset owner (Denscombe, 2010). The public asset owner belongs to a Portuguese municipality and has a mandate to manage all the social residential buildings as well as commercial spaces within those facilities. The building stock is composed by nearly 55 facilities built between early 1940's and 2012. These represent a total of nearly 4,500 houses. The public asset owner is responsible for the management of the building stock during operations and use. Usually, the design and construction stages are not managed by the public asset owner but are handled by other entities within the municipality or national agencies related with social housing. These entities later transfer the built assets for use by the public asset owner. As a result of this asset transfer process, the study identified significant knowledge gaps or total absence of project-related documents. Hence, the need for the definition of a strategy and development of procedures that could assure streamlined transfer of all relevant project-related information to the public asset owner.

Other corporate purposes of the public asset owner are social support, lease of houses, and maintenance of common areas of the buildings as well as exterior surroundings. The tenants are responsible for the maintenance of the houses, except where the defects are motivated by problems on or from common areas. This awareness is essential in understanding the boundaries and the type of construction elements and products to be maintained. Besides narrowing the scope of the construction process, it also has influence on the information requirements and economic impacts of the strategy. On the other hand, it was evidenced that the boundaries are somewhat "flexible" causing disturbance on criteria definition. This is due to the size and heterogeneity of the building stock. Furthermore, all claims and maintenance activities from 2013-to date are placed on a proprietary information system. This system supports all the claims and maintenance requests for a specific building or house, which is organised according to system or construction elements and the process follow-up (inspection, budget estimate, tendering (when applicable) and final report) until its conclusion. In addition, the system supports the management of house occupancy, definition of incomes and the required adjustments in relation to the number of households. This system was initially developed and improved according to business needs but it was found to be the main structure for the development of the BIM-based AM strategy. It also provides the data element to compare with other tools in terms of information levels and information requirements or definition.

4.2 Case Study Characterisation

As previously stated, criteria were set for the selection of the building/facility to be used as case study. These were related to the amount of information available from the design and construction stages. Furthermore, the representativeness of the facility in terms of construction solutions on the overall building stock, and the ability to track on-site all the maintenance activities that have been developed since commissioning were crucial for this case study selection. This led to the appraisal of one of the most recent facilities built on the municipality. The building is referred to as “RF_50 – Residential Facility_50” in this study. The architectural design was developed in 2008 and construction started in 2010 (MEP design-build contract). The total project sum for the MEP design and construction represented nearly € 500,000.00. The first houses were occupied in 2012. In terms of volume, the facility is a single building with two floors comprising of 12 houses. The building deployment area is 400 m^2 and the total construction area is around 1,050 m^2. It is a reinforced concrete framed structure with masonry infilling walls and Goth coated flat roof. The facades are finished with ETICS and the window and door frames are made of lacquered aluminium with double glass. The common areas are finished with painted plaster on walls and ceilings and the floor with ceramic tiles.

4.3 Information Management Strategy

The case study lacked existing procedures to manage building information across asset development stages. Therefore, in order to structure the operational information requirements of the asset owner, a first level analysis is conducted. This led to the definition of aspects that are found to be relevant for asset operations and maintenance. The schematic analysis utilised is presented in Table 2.

Table 2: Information management strategy schematic structure

S/ No	Themes	Institution
1	Sector	Residential
2	Strategy	Priority Definition
3	BIM Data Perspective	COBie (ifc)
4	General Structure	1. Attribute-sets definition. 2. Individual elements covered in Object Category below. 3. Individual systems or objects according to business needs
5	Object Category	1. Structure 2. Building fabric shell 3. Plumbing - common areas 4. Lighting - common areas 5. Fire protection 6. Exterior windows 7. Photovoltaic system

The above analysis (Table 2) highlights that the business sector of the public asset owner has a clear relationship with nature and type of information needs. Therefore, this factor will clearly impact the development of the BIM-based AM strategy. The analysis reinforces the logic or premise that information requirements are directly related with the mandate of the entity. Furthermore, there have been maintenance activities that have been carried out by tenants without the knowledge of the public asset owner such as painting, tiling, and electrical plugs, to name few. Hence, the study notes that without total control over all building elements and the execution of maintenance activities, the definition on the BIM-based AM strategy will have a limited scope.

4.4 Information Requirement Analysis

The proprietary information system supports all claims and maintenance activities carried out by the public asset owner. It also deals with substantial information from "Facility" to "House" level. Even though it was not structured and envisaged for BIM-based processes, it meets most of the COBie-level information requirements for the "Facility", "Floor" and "Space" worksheets. The system manages maintenance operations without the technical detail or data of the building components. Despite the two-level structure for categorisation of maintenance actions, the datasets were not suitable for populating the "Component" and "Type" worksheets. For the identification of the of the requirement type data, the study evaluates documents produced at design and construction phases, namely; bill of quantities, drawings, specifications and on-site inspection reports and visits. In addition to these information sources, there are other documents developed by the public asset owner that helps to systematise relevant data in relation to the facility. From these documents, more than 50 components to be maintained by the public asset owner were identified. These are referred to as "management documents". Furthermore, for the purpose of implementing COBie, standard breakdown structures were identified and incorporated into the process either from legal documents or AECOO industry standards. Figure 4 presents the summary of information sources available within the public asset owner in order to fulfil the main information fields of the COBie worksheets from "Facility" to "Type" level.

Facility	Sources of information	Comments
Name	• Δ □ ◊	different names - standardization is required
Category	□ ∷	
Project Name	Δ ◊	
Site Name	•	
Area Measurement	□	
Description	∷	
Project Description	• Δ □ ◊	
Site Description	• Δ ◊	
Phase	∷	

Floor		
Name	• Δ ◊ ✱	
Category	• ◊ ✱	
Description	✱	
Elevation	◊ ✱	
Height	◊ ✱	

Space		
Name	◊ ✱	
Category	✱ ∷	
Floor Name	• Δ ◊ ✱	
Description	• ◊ ✱	
RoomTag	•	not for all
UsableHeight	◊ ✱	
GrossArea	◊ ✱	
NetArea	◊ ✱	

Zone		
Name	•	
Category	• ◊ ✱	
Space Names	◊ ✱	
Description		need to be defined

Component		
Name		requires asset classification
Type Name	• ◊ ✱	
Space	◊ ✱	
Description	◊ ✱	
SerialNumber		requires asset classification
InstallationDate		not traceable in most situations
WarrantyStartDate	• Δ	
TagNumber		requires asset classification
BarCode	✱	in some might be dificult to achieve
AssetIdentifier		requires asset classification

Type		
Name	• ◊ ✱	
Description	◊ ✱	
AssetType	◊ ✱ ∷	
Manufacturer	◊ ✱	
ModelNumber	◊ ✱	
WarrantyGuarantorParts		depend of products
WarrantyDurationParts	□	
WarrantyGuarantorLabor		not traceable in most situations
WarrantyDurationLabor	□	
WarrantyDurationUnit	□	
ReplacementCost	•	inputs from the system not from the product manufacturer
ExpectedLife		(*)
DurationUnit	□	
WarrantyDescription		need to be defined
NominalLength	◊ ✱	
NominalWidth	◊ ✱	
NominalHeight	◊ ✱	
ModelReference	◊ ✱	in some might be dificult to achieve
Shape	◊ ✱	
Size	◊ ✱	
Color	◊ ✱	
Finish	◊ ✱	in some might be dificult to achieve
Grade	◊ ✱	in some might be dificult to achieve
Material	◊ ✱	in some might be dificult to achieve
Constituents	◊ ✱	in some might be dificult to achieve
Features	◊ ✱	in some might be dificult to achieve
AccessibilityPerformance		not defined
CodePerformance		not defined
SustainabilityPerformance		not defined

•	Claim system
Δ	Management documents
□	Legal documents
◊	Project documents
✱	Site inspection
∷	Standards and references

Figure 4: Information sources to fulfil COBie worksheets from "Facility" to "Type" level

The above (Figure 4) information source and requirement analysis helped in the development of the BIM-based AM strategy. The information available allows setting additional attributes to most of the worksheets. In terms of data consistency, discrepancies were identified between the claims system and the project documents. On-site inspection evidenced that data in the project documents were accurate, meaning that some errors might have occurred in entering the data onto the system. Several source definitions were observed for the “Project Description” field, meaning that a standard description needs to be set and updated on all systems and documents. “Component” and “Type” worksheets generally rely on project documents and site inspections. Hence, the developed strategy recommends the re-structuring of these activities in order to take advantage of the opportunity by executing them concurrently with other activities such as the identification of the condition of building components. However, some information fields lack “Component” and “Type” level information. This is found to be the second step and the core of the BIM-based AM strategy because it relies on the definition of the data structure and BIM data perspective by the asset owner. This analysis provided better understanding regarding different aspects of the case study. The first is the discovery that there is a general lack of project-level information. This means that the public asset owner is managing facilities without the entire knowledge of its components. Second, is the understanding that the claims system constitutes an essential tool for managing the facilities but little value is derived for the purpose of general AM. Hence, the strategy highlights the need to address issues regarding project-level knowledge gaps at three levels: a) definition of the basic project information needed; b) tracking data for each facility across systems and project documents (where or if the information is available); c) taking advantage of the claims system either by correcting discrepancies or by improving the information reports and to develop interfaces that are BIM oriented.

5. Conclusions

The purpose of the paper is to investigate the initial stages of the development of a BIM-based AM strategy and to frame, evaluate and test the defined strategic approach based on requirements and established AM development stages set by the asset owner. For the purpose of the BIM-based AM strategy definition, the existence of a claims system is found to be useful as it structures relevant asset information. Another advantage is that it is based on current staff work processes and as a result, there would be no need for process re-engineering. Consequently, this would foster and facilitate the evolution and implementation of new or additional systems by the public asset owner. Notwithstanding, the claims system has its downsides. The study finds information discrepancies that need to be resolved within the system. Furthermore, the case study highlights the challenges and the need to define information requirements including further developments required to deliver a minimum AM strategy based on COBie. The study identifies that the development of the AIM will rely on extensive on-site inspections either to implement the asset categorisation strategy or to identify relevant asset data to fulfil COBie requirements. Also, it highlights the need to re-structure activities and execute them concurrently in order to take advantage of the whole process. The research, methodology and outcomes led to distinct results:

- development of understanding and improved awareness of the difficulties of implementing the defined BIM-based AM strategy in a practical case study (effort, knowledge gaps, others);
- generic barriers and obstacles in terms of general implementation to all building stock managed by the public asset owner;
- direct uses of the strategy and benefits towards operation and maintenance actions;
- business value of BIM (across building maintenance actions, major and minor refurbishment actions, as well as new construction processes).

In conclusion, future studies will be developed based on information delivery guidelines for the public asset owner in executing preventive maintenance actions, major and minor asset interventions as well as the information requirements and performance of technical solutions for new-build construction processes.

References

Borrmann, A.; König, M.; Koch, C. ., & Beetz, J. (2018). *Building Information Modeling - Technology Foundations and Industry Practice*. (J. Borrmann, A.; König, M.; Koch, C.; Beetz, Ed.) (Springer). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-92862-3_1

BSI. (2014a). *Specification for information management for the operational phase of assets using building information modelling — PAS 1192-3:2014*. London: The British Standards Institution 2014; BSI Standards Limited 2014.

BSI. (2014b). *Collaborative production of information – Part 4: Fulfilling employer's information exchange requirements using COBie – Code of practice – BS 1192-4:2014*. London: The British Standards Institution 2014; BSI Standards Limited 2014.

Carbonari, G., Stravoravdis, S., & Gausden, C. (2015). Building information model implementation for existing buildings for facilities management: a framework and two case studies. *Building Information Modelling (BIM) in Design, Construction and Operations*, *1*(June 2016), 395–406.

Cavka, H. B., Staub-French, S., & Poirier, E. A. (2017). Developing owner information requirements for BIM-enabled project delivery and asset management. *Automation in Construction*, *83*(September 2016), 169–183. https://doi.org/10.1016/j.autcon.2017.08.006

Denscombe, M. (2010). *The good research guide: for small-scale social research projects* (4th ed.). Maidenhead, Berkshire, England: McGraw-Hill International - Open University Press.

Deshpande, A., Azhar, S., & Amireddy, S. (2014). A framework for a BIM-based knowledge management system. *Procedia Engineering*, *85*, 113–122.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM Handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors* (2nd ed.). Hoboken, New Jersey, United States of America: John Wiley & Sons, Inc.

Love, P. E., Matthews, J., Simpson, I., Hill, A., & Olatunji, O. A. (2014). A benefits realization management building information modeling framework for asset owners. *Automation in Construction*, 37(1), 1-10.

Grussing, M. N. (2013). Life Cycle Asset Management Methodologies for Buildings. *Journal of Infrastructure Systems*, *20*(1), 04013007. https://doi.org/10.1061/(asce)is.1943-555x.0000157

Hjelseth, E, & Mêda, P. (2016). Is BIM-based product document based on applicable principles?—practical use in NW and PT. In *eWork and eBusiness in Architecture, Engineering and Construction - Proceedings of the 11th European Conference on Product and Process Modelling, ECPPM 2016*.

Hjelseth, Eilif. (2017). BIM understanding and activities. *WIT Transactions on The Built Environment*, *169*, 3–14. https://doi.org/10.2495/BIM170011

Hossain, M. A. (2018). BIM for Existing Buildings: Potential Opportunities and Barriers. *IOP Conf. Ser.: Mater. Sci. Eng. 371 012051* doi: 10.1088/1757-899X/371/1/012051

Kassem, M., & Succar, B. (2017). Macro BIM adoption: Comparative market analysis. *Automation in Construction*, *81*(April), 286–299. https://doi.org/10.1016/j.autcon.2017.04.005

Korpela, J., Miettinen, R., Salmikivi, T., & Ihalainen, J. (2015). The challenges and potentials of utilizing building information modelling in facility management: the case of the Center for Properties and Facilities of the University of Helsinki. Construction Management and Economics, 33, 3-17. doi:10.1080/01446193.2015.1016540

Mêda, P. (2014). *Integrated Construction Organization – contributions to the Portuguese framework*.

Porto University Faculty of Engineering.

Munir, M., Kiviniemi, A., & Jones, S. W. (2019). Business value of integrated BIM-based asset management. Eng., Const. and Architectural Management. doi:10.1108/ECAM-03-2018-0105

Parsanezhad, P., & Dimyadi, J. (2014). Effective facility management and operations via a BIM-based integrated information system. *Proceedings of CIB Facilities Management (CFM) 2014 Conference*, 21-23 May, 2014. Copenhagen, Denmark.

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings - Literature review and future needs. *Automation in Construction*, *38*(March), 109–127.

Xiong, X., Adan, A., Akinci, B., & Huber, D. (2013). Automatic creation of semantically rich 3D building models from laser scanner data. *Automation in Construction*, *31*, 325–337.

‘Facilities Management’s Adoption of Building Information Modelling within the National Health Service’

Dean Douglas[1,*] and Marianthi Leon[1]
[1]Robert Gordon University
email: d.j.i.douglas@rgu.ac.uk

Abstract

As the UK's National Health Service (NHS) turned 70 years old in 2018, there have been rising questions about its future, while it continues to run a budget deficit. Now faced with doing more with less, it is imperative the NHS finds more efficient ways of working in almost all respects to ensure its longevity. An area where this is particularly true is the way in which it maintains its built assets. Concurrently, Building Information Modelling (BIM) continues to spur ever greater productivity and efficiency in the Architecture, Engineering and Construction industries. The information generated and collected during a construction project has the potential, if utilised, to aid in the more cost-effective running of an asset.

This research examines Facilities Management’s (FM) adoption of BIM within the NHS. Assessing the current awareness and understanding of BIM and exploring the barriers to adoption and what could be done to alleviate these issues. The research methodology comprised of; a comprehensive review of literature on the topics, in particular looking at trends in the NHS FM and the wider FM industry's approach towards BIM integration; an online questionnaire distributed to facilities managers in the NHS and other healthcare organisations within the UK; and a series of interviews with Facilities Managers within a number of NHS trusts and Boards as well as prominent advisors to these organisations.

From the research conducted, various issues are discussed that were highlighted as obstacles to BIM adoption. Issues such as; data and information management throughout a building’s lifecycle; the embrace of new technology for the FM; the current organisational hierarchy and structure both in the NHS and its FM departments; the image problem that FM professionals face and the resulting lack of representation in key decision making processes; the availability of investment into the development and adoption of BIM within NHS FM and possible funding options that could incorporate BIM such as Private Finance Initiative (PFI); and the irregular implementation of the UK BIM level 2 Mandate.

In conclusion, while there have been a number of barriers to the adoption of BIM in the NHS FM made apparent during the research, given that the process of implementation is still very much at the early stages, there will still need to be a great deal of research and development carried out on how the NHS Facilities Management and the wider Facilities Management industry will adopt BIM. However, if this is done now then it will allow for the groundwork to be correctly laid down for future implementation.

Keywords: Building Information Modelling (BIM), Facilities Management (FM), Healthcare

1. Introduction

Building Information Modelling (BIM) application has the potential to greatly reduce waste, reduce time and cost overruns, lower carbon emissions and in the future has the potential to give end users the ability to better utilise the built assets (UK. HM Government, 2013). The adoption rate of BIM in the UK has been spurred on by the Government's 2011 and the subsequent 2016 update of the Government Construction Strategy, which mandates the use of BIM Level 2 on public sector construction and infrastructure projects. A quarter of all construction output in Britain comes from the public sector. As a result of this, the government is acting as an informed client in relation to BIM adoption, hence, benefiting from its impact (McPartland 2017). Not only does the mandate aid the adoption of BIM in the construction industry, the government itself greatly benefits from the mandate, as it aims to empower clients and their capability to procure better built assets. Two of the key principles of the Government Construction Strategy that will drive this change are: greater collaborative working, and the early involvement of the supply chain and the future operators of an asset (Mills 2016).

The National Health Service (NHS) in the UK currently holds £44 billion in assets (Arcadis 2016) and it is estimated that around £30 billion is spent on facilities and estates management within the NHS each year (CENSIS 2018). Following the 2008 financial crisis and the ensuing economic downturn, as well as the strict austerity measures implemented by the UK government, there was much more demand for added value within public sector spending. Much like various other public sector professionals, facilities management (FM) professionals found themselves in the position where they had to do more with less, hence, the public projects FM sector searching for new and innovative opportunities to improve working and aid their business strategies (O'Brien 2017).

During the recent Embracing Technology to Move FM Forward (2018) report, the UK industry body of British Institute of Facilities Managers (BIFM) acknowledged that technological advancement opportunities such as BIM, Computer Aided Facilities Management (CAFM) systems and Building Management System (BMS) and also a growing amount of emerging technologies such as people analytics and Artificial intelligence (McDonald 2017) are all likely to play a big role in FM in the future and streamline the way in which built assets are managed. However, there is an uncertainty and a number of different opinions in the industry about what type technologies should be adopted and the changes these could bring about (NBS, 2018). As with any industry that is seeking to embrace new technology, a certain degree of new understanding must be developed. It is likely that there will be a combination of numerous technologies that complement one another and allow for the FM to carry out their duties in the most efficient way possible (Newton et al, 2015). Although the adoption and integration of numerous technologies might also serve to create more problems for the industry as current awareness of some of the technologies still requires a great deal of development. This issue has already been identified by the industry as a barrier to their development and is thought that it might be in part due to the disruption to current working styles that any new systems might bring about (Watson 2016).

The current ways of working and the standing of the FM professionals in the NHS is traditionally split into two factions, hard and soft FM (NHS Property Services 2015), while the differences between these styles of working and the variety of services that they provide further highlight the complex issues that the FM industry faces in BIM adoption (Kelly 2018). As well as the internal structuring of FM the external image of the profession is an issue with allied industries and in the general public failing to understand what FM really entails (Moriarty, 2018) often oversimplifying its work. BIFM is currently exploring resolutions to this one of which is the aligning of FM with other professions such as HR, marketing or sales in what is referred to as workplace FM. Another way in which this is being tackled is the use of the Government Soft Landings (GSL) which strives to involve an assets FM in the design and construction phases of a project and also the design and construction in the operation.

Use of BIM within NHS FM systems has the potential to help the health service maintain and develop its assets, as well as providing cost saving benefits to allow government cost saving targets to be met. One potential applicator explored for BIM in the whole lifecycle of an asset could be via the use of Privately Funded Initiatives (PFI or NPD in Scotland), the Department of Health and Social Care (DoHSC), who NHS belongs currently holds the greatest capital value of PFI projects of any government department (UK. HM Treasury, 2018). Generally, under PFI contracts private sector companies finance, building and maintain assets used by a government department and are required to meet Key Performance Indicators (KPI) in order to receive reimbursement via the unitary payment system (NHS Scotland, 2009) which normally extends over a period of 20+ years. it is thought that through the KPI mechanism BIM could be specified and implemented over the entirety of an asset's life cycle. The paper aims to gain a deeper understanding of the current barriers to the future adoption of BIM within the NHS Facilities Management teams through review of theory and empirical data analysis to address the following objectives:

- Understand the current restrictions to the use of BIM within FM in the NHS and identify current legislation that may need to be updated, reduced, created or removed to enhance the use of BIM within FM.
- Evaluate the current industry understanding of BIM and its uses/benefits to the FM industry while assessing the FM industry's current and future abilities and strategies to adopt further BIM working within FM healthcare delivery.
- Examine whether the use of Privately Funded Initiatives (PFI) has an influence on the adoption of BIM.

2. Methodology

It was decided that a two-fold approach would be adopted for the research; the first half of the research was to create an online questionnaire and then distribute it to the relevant facilities, asset and estate managers in healthcare facilities throughout the UK. The second stage of the research conducted was a series of structured interviews both in person and via telephone to facilities and estates managers in the NHS Trusts and Boards across the UK as well as a select number of industry-specific BIM specialists from both the FM industry and in healthcare facilities management.

2.1 Questionnaire

During background research it became apparent that there had been a number of comprehensive surveys and polls conducted that sought to establish the awareness and understanding that facilities managers possess of BIM. In turn, the questions asked in this survey built upon a similar survey conducted by BIFM in August of 2017 (Ashworth & Tucker, 2017), which sought to assess the awareness and understanding of BIM in the FM industry as a whole. The majority of questions that were asked in both surveys were of a quantitative nature, which enabled the direct comparison of the awareness and understanding of BIM in the NHS FM with that of the industry as a whole. The survey took the format of an online self-completion questionnaire, the online distribution allowed for the quick and effective collection of data from a large sample group (Wisker, 2007). The survey was comprised of twenty questions that were selected or created as to adhere to the primary objectives of the research that were outlined at the offset. Using a series of closed questions that asked participants to select from given answers or to rank options, the results were mathematically analysed allowing for trends to be established and the direct comparison to be made with the previous survey.

2.2 Interviews

It was highlighted that the need for a first-hand insight into the ability of the FM within the NHS to adopt BIM would be essential in this research. In light of this, a series of semi structured interviews with relevant professionals within FM in the NHS and relevant bodies were conducted. The series of interviews run concurrently with the survey, with most participants contributing to both. The majority of the interviews were conducted face-to-face, with a small number being carried out over the phone. It was decided to conduct the interviews, where possible, face-to-face, as it was felt that it had the potential to provide more detailed answers. The interview process sought to obtain as much qualitative data as possible; in order to achieve this, a detailed series of open questions were formulated in accordance with the research aim and primary objectives. These were then structured into a schedule of questions to be put forward during the interviews. It should be noted that while there was a question schedule, it was not always strictly adhered to and the interviewer was at liberty to change the order if they saw fit. When necessary, follow up questions were also asked to elicit more thorough and in-depth answers or to seek clarification.

3. Results Analysis

3.1 Questionnaire Analysis

The survey began with overwhelmingly positive results, there was the apprehension that there may be a lack of understanding at a basic level that had been derived from the literature and language used when talking about BIM in the FM industry. However, when asked had they heard of, BIM before the survey, 96.7% of respondents stated that they had. Following this, participants were asked if they thought that BIM will have a significant impact on facilities management in the NHS. This was posed as a neutral question not requiring the participants to decide whether it would have a negative or positive effect on FM; 73.3% of respondents stated that they thought it would have a significant effect but perhaps more surprisingly 10% of respondents selected they felt it will not have a significant impact on FM in healthcare. In addition, a number of participants (16.7%), stated they were still unsure of BIM's impact. Directly following this, participants were asked if they thought that BIM will help them in their delivery of FM and results favoured BIM with 80% of respondents thinking that it would, however the number of participants that answering that BIM would not help them rose to 13.4%. These initial questions show that while there is an understanding of BIM within the industry, it is not cohesive and there is still work to be done to demonstrate the benefits of BIM adoption to all.

The lack of consensus was further shown when participants were asked to indicate the time scale upon which BIM will have an effect, with just as many people (23%) stating that they thought it would take 3-5 years to implement, as said it was already having an effect, this may be due to the difference in the different subdivisions of the NHS Estates Departments that this survey was issued to, such subdivisions as Capital Planning are likely to have encountered BIM already as they are involved in the procurement of new assets and are often the drivers for the implementation of BIM in the NHS, on the other hand the Soft FM providers are unlikely to have experienced BIM. But by far and large, more than a third of participants (36.7%) thought that it would take 5 years or more for BIM to take effect, indicating that there is still work to be done before the majority of FM feel that BIM will take effect. This theme continued when asked whether they considered their organisation to have adopted BIM at a strategic level, 60% answered that they did not, showing a lack of awareness and understanding at strategic decision-making level or that there is not the drive from the higher levels that is required for implementation.

As part of this survey participants were required to select five statements that they felt best showed the restrictions that the organisation faced in the adoption of BIM, they had 13 defined statements to choose from and the additional option to contribute their own. The top five results saw the repeat of answers; software and training, but also highlighted additional issues such as the traditional work culture within FM. This statement was included in this question as in early conversations with professionals, it became evident that there may be an issue with long term staff members being unwilling to alter the status quo as they feel it is a system that works, again potentially showing the need for training of frontline staff. These results were echoed when participants were openly asked about what they thought would better their organisations implementation of BIM with points such as training programs, and FM software that incorporated BIM being the top responses showing these issues are those that concern the FM by far the most. The reoccurring issue of training shows that while there is an understanding of BIM, it may not be in-depth nor widespread, it also creates a feeling that there may be an uncertainty in the current knowledge of BIM that the FM industry holds.

3.2 Thematic Analysis of Interviews

Whilst the interviews were conducted in a semi-structured manner, the open nature of the questions fielded to the interviewees meant that the responses given varied greatly in the issues that they highlighted and the future solutions to issues that were discussed. Due to this it was opted to conduct a thematic analysis of the interviews, where recurring themes were deduced and expanded upon.

3.2.1 Culture Change

One of the largest issues that arose out of the interviews with nearly all participants making comment on the issue in one form or another, was the systemic cultural changes that are required in the FM sector of the NHS and in the broader FM industry. Due to the proportions of this issue it was decided to further subdivide it into three distinct parts; the way in which FM services in the NHS are provided, the early involvement of the FM in a project and the standing of the FM role.

The picture that was portrayed of how the NHS conducts its FM services indicated there are clear divisions between the multitude of services provided under the single estates department umbrella. FM services both in the NHS and the general FM industry tend to be split into two; hard and soft, however in the NHS it seems that even in the hard and soft factions there are silos of working and information with little to no inter working. One participant stated that they thought that the separation that had been made between hard and soft FM within their organisation was counterproductive. However, there was also the counterargument made that due to the large scale of delivery and the geographical distribution of the services that integrated, working of FM was not entirely feasible. In spite of this, it is clear that for the benefits of BIM adoption to be holistically felt then collaborative working within the Estate Department was crucial.

Another alteration to the current FM working culture that is required is for the implementation of the GSL process as part of the wider BIM implementation. FM professionals must understand the later benefits of their early involvement during the design and construction stages and how it could lead to a better functioning asset. However, when speaking to HFS it was said that in past instances where the FM had been included in earlier processes it had been difficult for them to make active contributions as the nature of FM day-to-day working can be quite reactive and, in the moment, rather than ‘preparing for the future’. It was also thought that perhaps this is due to the fact that they are simply not allocated the time for this and was considered additional to their daily workload. In later interviews it became evident that this might not be the case across the NHS with other interviewees stating that in their personal experience being included at the earlier stages of a project they felt that they could make valid additions. Making it clear that there is the potential for the different Boards of the NHS to learn from one another in this process, if they were to actively share their ways of working.

The standing of the FM profession in the NHS's organisational hierarchy, was an issue that emerged repeatedly, with the phrase 'not in the boardroom' being referenced. This is in response to a feeling that FM professionals are often undervalued and unable to actively contribute to corporate level decision-making and attain additional resources as they are not seen as being part of the primary objectives of the NHS, despite the business-critical nature of their activities. One participant stated that “FM is at the bottom of the pile and in the case of PFI, the private FM provider is even further below them." For BIM to be adopted, it is first necessary to realise that FM could be a main driver of efficiency and cost saving measures for the NHS.

3.2.2 Education

To incite such a large cultural change within the NHS a detailed education programme is required: currently it is clear that heads of Estates and Facilities Departments realise the advantages of BIM but are restricted in implementing it by the lack of understanding around them. Thus far in BIM adoption there has been a top down drive which has stemmed from a government level in the form of the mandate, on the other hand in the NHS this seems to be the middle out, with heads of departments required to demonstrate the benefits in relation to the cost and impact on the business plan to decision makers at an organisational level such. In several interviews it was mentioned that the challenge is making the board realise that BIM could greatly impact the way in which they deliver healthcare and streamline this service. In addition to this, they must also educate the workforce on how BIM will affect them highlighting that this is done in the name of productivity and efficiency, and not staff monitoring as has been the fear in the past. The largest part of the education process at this level will be showing staff how to utilise the new technology upgrade in both software and hardware, this is likely to be a major hurdle to overcome as previously the systems used were either very low tech or were paper exercises.

3.2.3 Technology Upgrade and Information Handling

For BIM to be successfully employed, then the NHS is likely to undergo a considerable technological revolution. On a number of occasions in interviews, participants spoke of their current BMS or CAFM systems' incompatibility with the way information is presented in BIM and its file formats. This means that either significant alterations need to be made to the current systems or completely new programs must be deployed. This sort of software update is unlikely to come alone and will need the hardware capacity and capability to match. The issues surrounding this sort of upgrade was highlighted by contributors stating that it is difficult for the Estates Departments to get any sort of tech upgrade as they are prioritised for primary services such as patient records and clinical administration. The future management and storing of information was a major concern for all of the professionals interviewed, with them voicing their apprehension about a number of issues. The predominant points covered were in relation to the maintaining of the BIM model's accuracy once an asset is operational, as there will be a constant flow of data being used and edited for an indefinite time period. This also raises the question of how this information will be stored and shared. Two scenarios were mentioned in relation to this; a central server with dedicated access points or a cloud based system that could be accessed via any device anywhere, both have their merits and both create further questions such as who has access and editing privileges to this information; it an information manager or is it a tech-savvy workforce? These issues arise from the lack of a clear vision as to how the FM can conduct itself in the BIM environment. An interesting aspect that emerged in the interviews were the different aspirations for the new technology that is to be implemented such as sensor monitoring, lifecycle maintenance, scheduling etc, coupled with the autonomous nature of the NHS bodies means that we could see very different outcomes.

3.2.4 The Cost of Implementation

The availability of capital investment for the upgrade of technology as well as the education required initially for the implementation of BIM is a major obstacle that has to be faced. The ROI of the initial money spent has to be realised and a clearly beneficial business case put forward to support it. Currently at NHS Grampian they are in the process of creating a business case that highlights the return on investment of the adoption of BIM to be put forward to the board. The education of key figures will play a large part in the successful acquisition of investment.

There was a great deal of scepticism around the issue of finance with a number of interviewees expressing the difficulties that both the NHS as a whole face as well as that of the FM. While at North Cumbria University hospital, it was said that the money needed for the upgrade of systems would not be received unless the payback was near immediate for it to be justified, giving the example of a system upgrade they were undergoing where the Board of the NHS Trust was given the option to spend a marginal amount more on the upgrade to save a great deal in the future. In spite of the clear benefits, it was opted to keep upfront costs to a minimum. A number of participants also discussed the need for a clear example similar to that of the NHS Pathfinder projects that were used to show best practice for construction projects or be provided with a proven mechanism to show the ROI.

Later, after the initial investment has been made and the new systems are in place and operational, the issue of what is to be done with older buildings in the NHS portfolio arise, some of which are over a hundred years old. There is a fear that surveying would be costly and disruptive to a hospitals' daily running. However, estates teams also made it clear that they could not solely rely on new builds to bring their FM into the BIM environment and there would be a time where it would be necessary to survey the existing buildings to some extent or run the risk of forever running a two-tier system.

3.2.5 The use of PFI

During the research, participants were asked about their thoughts on the ability of PFI and NPD (Scotland) to be the vehicle for change for BIM in the NHS. The responses received were varied. While most believed it was possible, they also thought that in its current use, a lot would have to change for it to be effective. Whilst at NHS Lothian it was stated that PFI has the potential to push through the use of BIM greatly in both the projects side and in the future management of the asset created but it is reliant on two crucial factors changing; firstly that the NHS and other public bodies need to be able to specify clearly what they want both in terms of a finished asset and the BIM management strategy into the future, and in turn they must also be aware of what they are specifying in real terms as in the past there have been misunderstandings. The second factor being that the private FM companies bidding for these PFI projects must also realise the benefits of BIM adoption prior to them putting forward a bid on a project. The use of PFI to implement BIM would not come without cost, it was mentioned by one FM in PFI professional in interview that while it is possible for the specification of the use of BIM in FM to be integrated into a PFI contract there would be a monetary cost to that and it would be factored into any bid and ultimately shouldered by the NHS.

4. Discussion

4.1 Data Management

There is great apprehension about the future management of BIM data, mostly in relation to how to integrate BIM into the current FM systems and ways of working, in particular the need for continual upkeep information throughout a building's lifecycle. Other concerns involve the storage and sharing of the data and an issue that arose repeatedly was how the existing NHS estate, the majority of which is over 30 years old (Arcadis, 2016) can be incorporated into the BIM environment.

One potential solution being pursued by HFS was the acquisition of a CDE for the use of the NHS Scotland Boards, so that at asset handover the Boards could centrally store the information generated in a structured and openly accessible depository that would be provided and maintained by the NHS itself. This would also serve as a Data bank of both project and operational information from across Scotland that could highlight lessons learned. However, even with the acquisition of a CDE, there is a great deal of work to be done in order to get the current data held, collated and organised in a manner that would make it of use. At this point there would also be a need to verify the validity of the information held, as there may be situations where the information is as designed or is of a previous iteration. During the research, it was said that this practice would only be the beginning of a process that would be likely be routinely required (every 2-3 years) once BIM is operational in FM to ensure that the information stored is current, up to date and most of all useful to those working with it.

As for the surveying and cataloguing of the existing estate, there is currently no strategy laid out or in development by the NHS as to how its Estates Departments will bring their existing estate into the BIM environment and are currently relying on the procurement of new assets to generate BIM information. While there are some examples of BIM models being produced for existing assets such as Northumbria University’s program which saw the surveying and creation of a BIM model of its Newcastle campus (Open BIM, 2012), it was felt that the NHS would require an exemplar project, specific not just to healthcare, but to the NHS itself.

4.2 Embracing Technology

During background research, the FM industry literature alluded to the FM being in a position to adopt new technology into their methods of working and it was thought that from such reports as the BIFM’s Embracing Technology to Move FM Forward (Ellison & Pinder, 2018) and Top Trends in Facilities Management (CBRE, 2017) that while adoption of technology was slow in the FM industry, it was nonetheless happening. It had seemed as if the FM was in a position to begin BIM integration into existing and emerging technology already using. In spite of this, during the interview process, it became apparent that there was still a great deal of work to be done and progress to be made in the area of embracing new technology into their daily working. Teams reported running rather antiquated and inadequate systems which leaked resources, with paper-based systems still widely being used. It may be that there has to be a digital overhaul of FM similar to that mentioned in the BIFM report (Ellison & Pinder, 2018) before the full benefits of BIM can be felt. However, it is possible that the NHS does not entirely represent the whole FM industry but interviewees that had worked in FM in and out of the NHS for a number of years, did not indicate that there would be any great disparity between the two. The position that the NHS estates and the broader FM industry find themselves in could be the result of the vast amount of new technology available to them that could aid in the delivery of the multitude of services that they provide under the FM or Estates banner.

4.3 Organisational Structure

In the earlier research, it was established that there are subdivisions within the FM industry, mostly in the form of the hard and soft FM providers, and because of this, there are differences in the levels of ability and willingness to adopt BIM between the two. This situation is no different in the NHS while hard and soft services are grouped under the Estates Department, it makes they are no more integrated: they remain fragmented and sometimes even at odds with one another. It was said in interviews that the currently separated hard and soft elements of FM delivery should be combined. There may also be an argument to be made to better integrate the Capital Planning faction of the Estates Department, as they are currently the ones leading the BIM implementation in the NHS. This would feed better into such BIM components as the development of the EIR and the use of the GSL. In particular, the day-to-day running would benefit from greater collaboration and shared process and technology. In order to achieve this, it will be necessary for changes to be made to the organisational hierarchy and separation of the NHS Estates Departments, so that they lend themselves to greater collaboration and interworking between their various deliverables. However, as it stands, the nature of FM delivery within the NHS seems to provide an even greater barrier to the adoption of BIM.

4.4 The Standing of FM

There is an image problem that the FM industry and its professionals have long been enduring, the misunderstanding of what their role entails, often being referred to as ‘the people looking after the building’ which greatly falls short of the reality. Due to this, often FM professionals are being left out of key strategic decision-making processes, that affect them or where it may have been valuable to have their input. This problem was even apparent in HFS’s BIM Development Group which is primarily comprised of Capital Planning members of the Estates Departments, despite it being said that the group had always been developing BIM in the NHS with a view of implementation in the operations stage. The BIM Development Group is not the only example of this occurring in the NHS, there is also the lack of Estates Department members in the NHS Digital organisation, which was purposely created to discuss and develop the integration of new and emerging technologies into the NHS ways of working to improve efficiency and productivity. This further highlight just how the standing of the FM greatly impacts their ability to bring about change and adopt new technologies such as BIM. This issue is so embedded that many industry governing bodies, both in the UK and internationally, offer schemes to improve awareness and understanding about the work FM conduct. However, there is some reprieve in sight with businesses slowly realising the importance of their built assets (Institution of Civil Engineers, 2013) and how they can improve their core business through better use of their assets. In turn, it is hoped that this will also bring about better acknowledgement of what the FM industry can provide especially in terms of optimisation of an asset which would further the BIM agenda.

4.5 Funding and Capital

The availability of investment into development and adoption of BIM within the NHS FM will have a large influence on the capacity to adopt and to what degree that emerging digital technologies can be incorporated into FM working. Throughout this research the possibility of the use of PFI as a catalyst for the adoption of BIM was explored: it was suggested that PFI did have the ability to integrate BIM into its contract and require FM providers to use BIM. The use of PFI to implement BIM in FM is dependent on two primary factors being achieved; the first being that NHS bodies procuring in this way must be confident in their ability to create a comprehensive specification outlining the desired use of BIM for FM over a prolonged period as PFI contracts normally last 20+ years (UK. HM Treasury, 2018). Secondly that any private sector company looking to take on the operations of such a project would have to realise the benefits of BIM use. It is likely that these hurdles could be overcome, however the use of PFI is likely cause backlash from the public, due to past endeavours (Moore 2018).

There is also the reality that any additional costs incurred by the private sector for the use of BIM or if they felt that they would hold a greater portion of the risk would result in this being accounted for in their tender and ultimately result in the NHS still paying more.

The capability to show ROI of BIM use in FM will be of vital importance when seeking capital investment from NHS bodies, since ROI will have to be included in a detailed business case that will be required as part of a proposal for NHS Boards. It must be remembered that the primary objective of the NHS is to provide medical care and funding will be prioritized towards achieving this. An option to stop this competition for funding between primary care and other activities, is to replicate NHS Property, which saw the creation of a separate private property company that is still owned by the public sector and oversees the development and maintenance of the NHS estates and guarantees fixed and regular funding (NHS Property Services, 2013).

4.6 The Mandate

One of the unforeseen upbringings was the sporadic application of BIM level 2 in the design and construction phases of NHS projects, with a number of participants highlighting that a variety of their recent and current projects had not used BIM level 2. It should be noted that while the UK BIM Mandate only came into effect as of 2016, the path to its instatement started back in 2011 with the GCS (2011). Nevertheless, the intention of applying it like this was to give public bodies time to adapt and equip themselves to be ready to apply in 2016 and great strides have been made towards this. However, it did become apparent in both the literature and research conducted, there is the question of what level of BIM should be applied to a project or sometimes if it should be applied at all. In Scotland, the Scottish Government have set themselves a project budget threshold of £4.32 million, any public procurement above this amount must be conducted in fully collaborative 3D BIM level 2 and anything below the threshold must perform an assessment to show whether BIM would be of benefit to the project (UK. Scottish Government, 2015). In doing this, there is the risk that BIM could be omitted from a project with relative ease in the name of cost of implementation and in turn leaving a gap in data of any future estate wide BIM model. It should be noted that it was suggested during the interviews that the lack of BIM or BIM level 2 on some projects was not entirely a result of strategic decisions made during the procurement but instead due to the adoption of BIM by the contractors, despite them having shown BIM competency in their BEP proposals during the tendering process. The issue of enforcing the mandate was a point that was highlighted by the NBS's National BIM Report (NBS, 2017) and during the interview series, both raising the question as to how the government would enforce the mandate and whether it would be required.

5. Conclusion

The process of implementation is still very much at the early stages and there will need to be a great deal of research carried out on the matter. However, if this is done now then it will allow for the groundwork to be correctly laid down for the future implementation. There are a number of barriers to implementation that the FM in the NHS must address if they are to fully adopt BIM into their asset management strategy: the updating of current systems such as CAFM or BMS to include new digital technologies that would complement and utilise BIM information; the reshuffling of the current Estates Departments divisions and hierarchy to all for greater interworking and collaboration between team members; the ability to show ROI is essential when seeking capital investment for BIM development but it must form part of a robust business case to ensure that that it can contest against funding allocations for primary care objectives; and the education of a multitude of NHS staff members, ranging from the board members to frontline staff. Some of the obstacles that have been highlighted are already beginning to be addressed such as the issue of data storing and structuring, which is likely to resolved through the acquisition of a central NHS CDE, this in turn will likely raise the need for the existing assets to be incorporated into the system requiring a surveying strategy.

Over the course of the research, it was said on a number of occasions that the NHS would benefit greatly from a best case example and while there are projects that have incorporated such elements, none are in the NHS, and it was expressly stated that any example project provided would have to be in the NHS and even further, be specific to any one of the devolved nations' NHS. In the future we could see a number of very different responses to these current barriers in each of the NHS Boards and Trusts as a result of their autonomous nature meaning that they could end up taking contrasting approaches to BIM adoption.

An issue that not only the FM will have to address but also the AEC industries as well as legislators; is to ensure that the BIM level 2 mandate is being upheld and if not the options for enforcement. It is crucial that full BIM level 2 is continued to be applied to as many projects as possible now, so that the benefits of future adoption of BIM in FM can be felt.

References

Arcadis, (2016). Arcadis calls for better use of Estate to improve NHS finances and patient care. [online]. UK: Arcadis. Retrieved from https://www.arcadis.com/en/united-kingdom/news/latest-news/2016/3/arcadis-calls-for-better-use-of-estate-to-improve-nhs-finances-and-patient-care/

Ashworth, S. & Tucker, M., (2017). FM Awareness of Building Information Modelling (BIM). UK: BIFM.

CBRE, (2017). Top trends in facilities management. UK: CBRE.

CENSIS, (2018). Smart monitoring for building and property maintenance. [online]. UK: CENSIS. Retrieved from https://censis.org.uk/censis_projects/beringar/

Ellison, I. & Pinder, J., (2018). EMBRACING TECHNOLOGY TO MOVE FM FORWARD. UK: BIFM.

Institution of Civil Engineers, (2013). Leveraging the Relationship between BIM and Asset Management. UK: Institution of Civil Engineers.

Kelly, G., (2018). BACK TO BASICS – THE WHAT, HOW AND WHY OF BIM AND FM. [online]. UK: CIOB. Retrieved from http://www.bimplus.co.uk/people/back-basics-what-how-and-why-bim-and-fm/

McDonald, J., (2017). 4 TECHNOLOGIES IMPACTING MODERN FACILITIES MANAGEMENT. [online]. USA: iOffice. Retrieved from https://www.iofficecorp.com/blog/4-technologies-impacting-modern-facilities-management

McPartland, R., (2017). What is the Government Construction Strategy?. [online]. UK: NBS. Retrieved from https://www.thenbs.com/knowledge/what-is-the-government-construction-strategy

Mills, F., (2016). UK Government Construction Strategy 2016-2020 Explained. [online]. UK: B1M. Retrieved from https://www.theb1m.com/video/uk-government-construction-strategy-2016-2020-explained

Moore, J., (2018). PFI deals are bleeding the NHS dry – some hospitals can't even afford to buy sutures to stitch up wounds. The Independent. [online]. Retrieved from https://www.independent.co.uk/voices/pfi-deals-nhs-struggle-recover-carillion-collapse-government-finance-private-firms-public-sector-a8165716.html

Moriarty, C., (2018). EFMC 2018 Day 2 AM. [online video]. 7th June 2018. Retrieved from https://www.youtube.com/watch?v=7GG6GrQWR5A&feature=youtu.be&t=2423

NBS., (2017). National BIM Report 2017. UK: NBS.

Newton, A., et al. (2015). THE FUTURE OF FACILITIES MANAGEMENT IN THE FACE OF GLOBALISATION. Global FM FOCUS. [online]. Retrieved from https://www.fsi.co.uk/pdf/news_215.pdf

NHS Property Services, (2013). Introducing NHS Property Services Ltd. UK: NHS Property Services.

NHS Property Services, (2015). Facilities management. [online]. UK: NHS. Retrieved from https://www.property.nhs.uk/what-we-do/facilities-management/

NHS Scotland, (2009). Estates and Facilities Benchmarking Project Phase One – Final Report. UK: NHS Scotland.

O'Brien, S., (2017). FIVE MINUTES WITH… PRESTON GAN, FACILITIES AND ESTATES, NHS GRAMPIAN. [online]. UK: FM Briefing. Retrieved from https://facilitiesmanagementforum.co.uk/five-minutes-preston-gan-facilities-estates-nhs-grampian/

Open BIM., (2012). BIM for Facilities Management- University Campus. UK: Open BIM.

Rhodes, C. (2018). Construction industry: statistics and policy. London, UK: UK Parliament Library.

UK. Cabinet Office, (2011). Government Construction Strategy. UK: Cabinet Office.

UK. HM Government, (2013). Industrial Strategy: government and industry in partnership Construction 2025. UK:HM Government.

UK. HM Treasury, (2018). Private Finance Initiative and Private Finance 2 projects:2017 summary data. UK: HM Treasury.

UK. Scottish Government, (2015). Building Information Modelling (BIM) Implementation Plan September 2015. UK: Scottish Government.

Watson, C., (2016). Embracing technology: why disruption shouldn't be a dirty word in FM. Workplace Futures 2016, Page 34-36.

Wisker, G., (2007). The Postgraduate Research Handbook (2nd Edition). UK: Red Globe Press.

BIM Model Asseveration: Definition and Supporting Tools

Felipe M. Oliveira[1*] and Eduardo T. Santos[1**]
[1]University of Sao Paulo, Brazil
[*]email: fmesq@usp.br [**]email: etoledo@usp.br

Abstract

In this paper, we introduce the concept of "BIM Model Asseveration", explain the rationale behind it and propose some alternatives for implementing ICT and normative tools for supporting this newly named action. The paradigm shift introduced in the evolution from traditional design practices, in which every information is intentionally inserted (i.e. drawn) on deliverables, to BIM-based methods (object-based design authoring, incremental model construction, team collaboration and model information consumption) is discussed. During the development of a BIM model, a lot of unrequired/unchecked information is introduced into it when objects are instantiated. This is particularly true in the early design phases, when there is still a lot of uncertainty about the final specifications of components and if manufacturer-supplied objects (i.e., non-generic) are used for modelling. This is because those objects usually have all or most of its properties filled with specific product data and high visual fidelity. This problem is implicit in BIMForum's LOD definitions: "Level of Detail can be thought of as input to the element, while Level of Development is reliable output."; a lot of data enters the model, but only a fraction of it can be safely consumed. How can users of a BIM model know if some piece of information found in the model is valid, checked and available to be consumed by other professionals during the design phase? How can the author of a BIM model protect oneself from unauthorized/early use of information inadvertently inserted in the model or still not thoroughly checked? The usual recommend practices in this regard are either tacitly consider all information in the model as valid or to use Model Element Author (MEA)/Model Element Tables (MET), part of an agreed BIM Execution Plan, as guides for what information is to be provided and may be consumed at specific milestones. Then we present both the procedure for asserting the validity of needed model information (properties and geometry) - to be performed before delivery of (federated) models to coordination or for sharing among other professionals - and the proposed terminology to represent it (BIM Model Asseveration). Support from BIM authoring software or CDE platforms for asseveration certainly would be useful but is still largely lacking. We propose some possible approaches for developing tools that could help in model asseveration. We hope naming this procedure and proposing implementation approaches may foster the offering of professional tools for asseveration in the AEC market.

Keywords: BIM, Asseveration, MET, LOD, MEA

1. Introduction

BIM (Building Information Modelling) is increasingly becoming the new standard way for building design development, although adoption levels still greatly varies among countries (Kassem & Succar, 2017). Unfortunately, many people still see BIM as an evolution of CAD (Computer-Aided Design/Drafting), i.e., as a tool, instead of the process or methodology that BIM really is (Migilinskas, Popov, Juocevicius, & Ustinovichi, 2013; ArchiStar, 2019). Based on this wrong assumption, their approach to BIM implementation is simply to replace their CAD tool by a BIM authoring tool, without changing their design and collaboration processes.

In the traditional or CAD-based design workflow, 2D drawing sheets documenting the design are produced. All elements on those sheets (lines, arcs, symbols, annotation text, etc.) are manually inputted in a CAD authoring tool, by the designer oneself or by an auxiliary draftsperson. As design progress through its standard phases (schematic design, design development, construction documents) more detail is added to this graphical documentation, strictly under the designer intent.

On the other hand, design using BIM authoring tools is not based on drawing individual graphic elements. Instead, 3D objects are instantiated into the BIM model from object libraries. These objects may feature not only very detailed geometry but also a complex set of properties properly filled with specification values from their manufacturers.

In later design phases, a designer may intently insert an object in the model representing a specific product chosen for the project, when object dimensions are final and all parameters will hold specified values. However, this same object may be used in earlier phases, when it is used only as a design intent placeholder, containing much more information than the designer has already decided about (Sacks, Gurevich, & Shrestha, 2016).

Different from 2D representations, a BIM model usually “appears precise and certain” (Abualdenien & Borrmann, 2019, p. 136), which leads to false assumptions on information validity.

Therefore, a BIM model may contain unverified data in its objects, differently from a CAD drawing where all information is derived from explicit designer input. A proper way to proceed for avoiding erroneous or unintended assumptions from this unverified information in the model is to consult the project Model Element Table (MET) which registers the intended Level of Development (LOD), at a given milestone, for each type of component in project BIM models (Bedrick & Reinhardt, 2019). The Model Element Table is also referred to as ‘Object Element Matrix’, ‘BIM Element Matrix’, ‘Responsibility Matrix – Information Deliverables’ among other denominations. Most BIM Protocols and Guides recommend to include a MET in the project BIM Execution Plan – BEP (Sacks, Gurevich, & Shrestha, 2016) to inform model authors what Level of Development (geometry and properties) is required at each milestone or design phase as well as to guide BIM model information consumers (e.g., other designers, consultants, etc.) on what information from the issued model they can rely upon at a given time.

An informal survey conducted by the authors among local designers and BIM managers in Brazil revealed that the majority of practitioners do not even know what a MET is, because it is not specified in the BEP of most projects. Even some BIM implementation consultants are not aware of this practice. It is suspected that the same behavior can be found in other markets. Among those professionals that do not use a MET, three alternative strategies were identified:

> 1.*Cleaning/zeroing the unused/undefined parameters in BIM objects they use and that come pre-filled with manufacturer or generic values*. This strategy avoids liability arising from the use of unverified information from the model but incurs in additional designer work for erasing values and may lead to miss original information from the object specification that may be need by the designer in later stages.
>
> 2. *Using generic objects and replacing them with specific or more detailed ones as the design progresses*. This strategy also implies continuous work from the model author for replacing components and also requires the availability or creation of several versions of a component (placeholder, generic, augmented generic, specific…). An additional drawback of this strategy is that the GUID (Global Unique IDentifier) associated with a component will be changed as the object representing it is replaced, leading to possible automated checking failures and tracking issues.

3. Keeping the unverified data on the objects and possibly facing liability for their misuse. Data validity is assumed or is inferred by consumers based on design phase or through explicit inquires to model authors. This strategy is seldomly practiced.

We infer these behaviors are due to the legacy of the formerly mentioned CAD-based design workflow on which all information in the graphic documentation is supposed to be valid as it is always explicitly entered by the designer. As BIM models replaces CAD drawings, the same assumption is kept (i.e., all data in a BIM model is to be trusted at all times); therefore, by this thinking, no unverified data should remain in the model.

The use of a Model Element Table from a project BEP to guide model authors and consumers has to be disseminated among practitioners as it is thought to be the most straightforward procedure for the authors and the safest behavior for model information consumers and, therefore, the recommend practice found on good BIM guides and protocols (Sacks, Gurevich, & Shrestha, 2016).

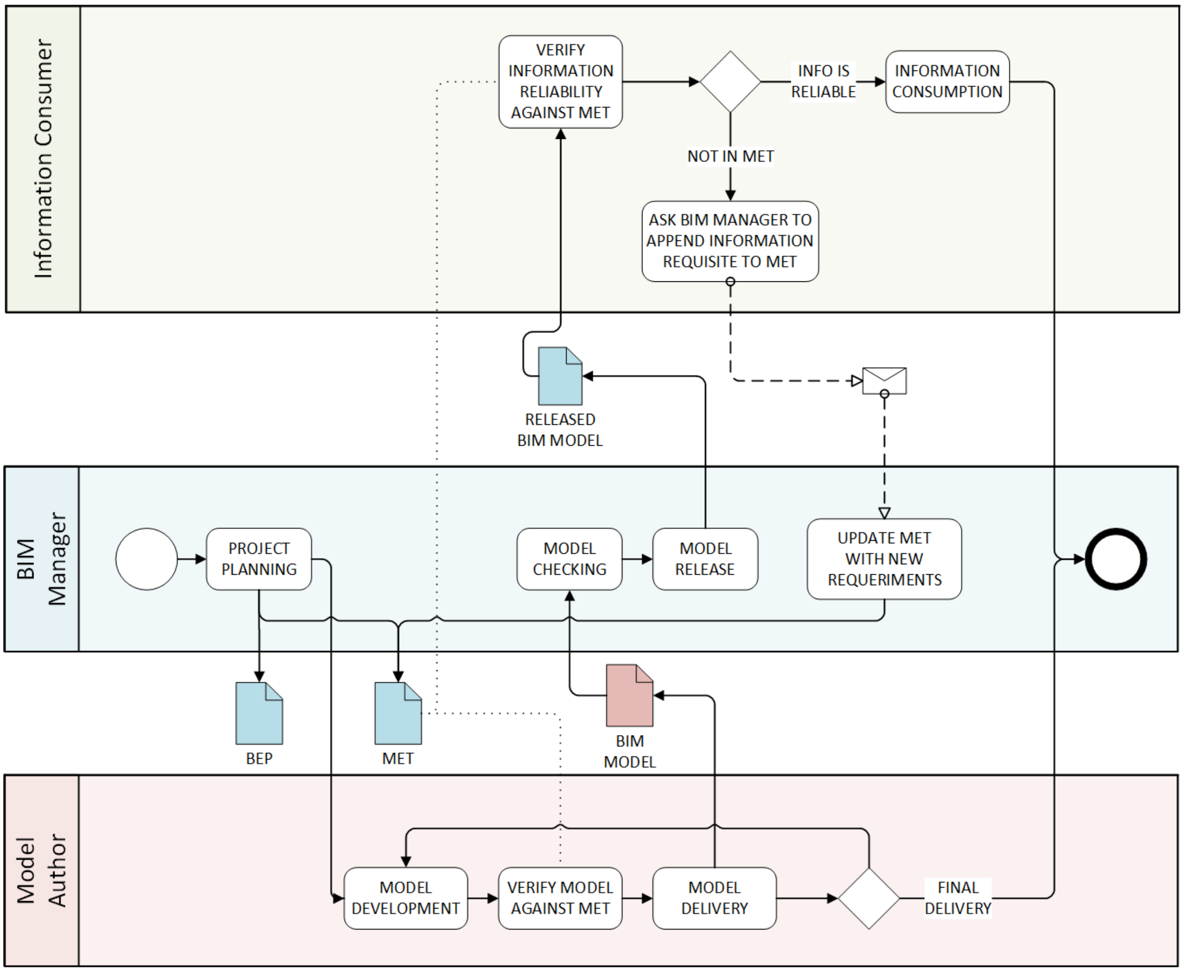


Figure 1: Simplified flow-chart of BIM project planning and model development / information consumption processes

Figure 1 shows a simplified flow-chart representing the processes of BIM project planning and design model development along with the resulting documents. The action of model delivery at a given milestone implies that the requirements for it are fulfilled and the information needed at that time can be consumed. Likewise, in the information-consumer side, having just the model is not enough for using its information, since the model can contain unverified information. Therefore, reliability verification against the MET is necessary, before model information use.

2. BIM Model Asseveration

Model Element Authors (MEA), responsible for creating/updating the information on a certain type of component in a BIM model, at a given project milestone/phase, as stated in a BEP, **should ensure** that the corresponding objects' size, shape, location, orientation and quantity are set according to the MET-specified LOD as well as all the required properties for the component, at that milestone, **are provided and verified**. Model information consumers are supposed to check the MET for assessing the reliability of a needed piece of information found in a model, at a given milestone, trusting that, if the required information is present in the model, **it was verified by the author**. This reliability on the validity of all the required information provided in a BIM model is the foundation of the MET-based system.

We propose that this still unnamed act of *asserting the validity of all required model information (including both geometry and properties)* to be called **'asseveration'** (Oliveira & Santos, 2019) .

BIM Model Asseveration is an action tacitly supposed to be performed before the delivery of federated models for coordination or sharing among other professionals. Giving a name to this procedure enhances awareness about it and stimulates research, certification, support, adoption and practice.

For a model to be considered asseverated, asseveration have to be performed in all model information from all components required by the MET for a specific milestone, according to the specified LOD/LOI (Level of Information).

It is important to differentiate *provisional information* from *unverified information* in a model. For example, a model object required to be at LOD 200 (i.e., "with approximate quantities, size, shape, location, and orientation" (Bedrick & Reinhardt, 2019)), at a given milestone, **still has provisional information after asseveration**, but now **it is not unverified** as before, and can be used for the specified LOD 200 purposes.

Also, it is worth mentioning that **asseverated models may contain invalid or non-checked information**, as long as that information is not among the ones required on the project MET for the corresponding project milestone model delivery date. That is why model information consumers are supposed to check the MET **before** using any data from the model. If the MET was properly constructed (i.e., registers all the information needed for all intended model uses at each milestone), this will not be a burden since consumers will have no interest in the non-required (and possibly invalid) information. If they do need some missing/unchecked information, then the MET has to be amended, specifying the new requirement at a future milestone (see Figure 1).

Asseveration is especially relevant for non-geometric properties. Even in a CAD-based workflow, practitioners are used to the fact that graphic elements representing the geometry of building components in a drawing are provisional at early design phases (e.g. the length of a wall or position of a door or column) and are cautious when using this information to advance their own work. However, they usually trust any textual information added to the drawing at any stage, and tend to do the same with attribute data found in model objects.

The concept of BIM model asseveration is tied to the model authoring workflow. In some workflows, in which all information in the model is intently inserted (e.g., all objects were created by the author) or represents the output of an automated and reliable process (e.g., structural components dimensioned by a stress analysis software), this information is considered asseverated. The same is valid when all required attribute values are checked when an instantiated object is inserted in the model.

Even in these workflows, in which the information input during model authoring is highly intentional (being very similar to the traditional methods of design, such as with 2D CAD), when it comes to collaborative BIM process with multiple delivery phases and BIM uses, there is still the challenge of managing and controlling what information must be in the model (and, also important, which can be consumed) after each design milestone.

Working according to the best practice, under the governance of a Model Element Table, may be cumbersome or unpractical, both for model authors and model information consumers. Depending on the amount of component types under the responsibility of a MEA and the quantity of properties on them which are required at a model delivery date by the MET, a lot of verification work is imposed on the designer. Even if there is not much variety on component types, but the quantity of instances in the model are large, the designer probably will benefit from some form of automation or support for the asseveration procedure. In the following section, some computer-based approaches to asseveration tools are proposed.

3. Proposed approaches for BIM model asseveration

According to a Design Science Research methodological approach (Dresch, Lacerda, & Antunes, 2014), after detecting a relevant problem ("lack of asseveration tools") and its characteristics, the authors investigated and proposed several artifacts (in this case, computer tools) which may solve the identified problem.

The proposed approaches for supporting asseveration described in this section address one or more of the following identified challenges to the task of asseverating a BIM model:

- Tagging asseverated information at attribute-level on each model object instance;
- Efficient look-up of requirements on a MET for a certain MEA, component type and milestone;

Reinhardt and Bedrick (2019, p.249) suggest using two properties (*Current LOD* and *Target LOD*) on all elements in a model as a way to identify those elements that have not yet reached the intended level (i.e., not been asseverated when *Current LOD* < *Target LOD)*. Having the *Target LOD* on each model instance also allows for a finer specification degree (instance level) than the component-type level in the lines of a MET. The problem with this approach is that LOD standard levels (100 to 500 in AIA/BIMForum system or 1 to 7 in the British PAS 1192-2:2013 (BSI, 2013), etc.) are mostly related to geometry and cannot inform about component attribute development status, i.e., is not at attribute level as needed.

3.1 Asseveration marker on properties of object instances

For the model author, the repetitive and error prone task of verifying each element's properties is critical for limiting author's liability risk. The amount of element properties to be verified can be enormous depending on the project size and complexity and intended BIM uses.

A checkmark style marker on each property of each object instance in the model to be ticked after asseverating the attribute (would help identifying verified items, avoiding rework on verifying it again. Figure 2 shows properties 'X' and 'Z' of Door 1 object have already been verified (i.e., asseverated) while property 'Y' was not yet. This scheme would make it possible to implement a filter for non-verified properties that are required for the next model delivery and ensure their verification or removal before release.

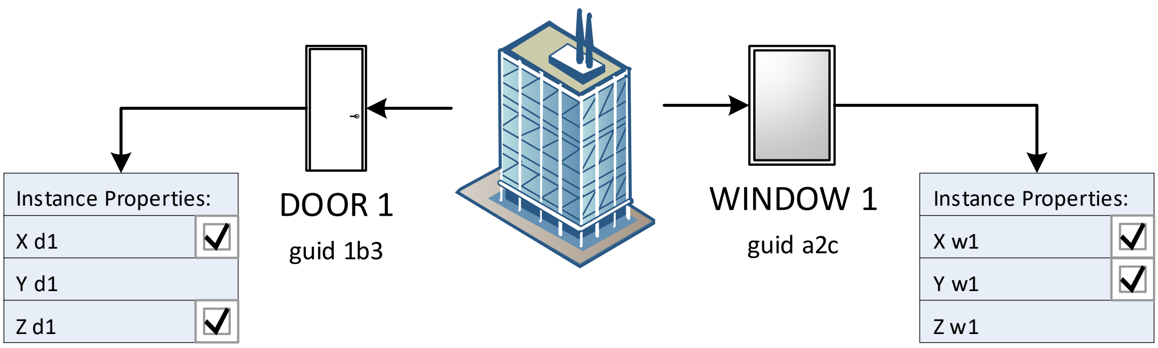


Figure 2: Tagging system for instance properties asseveration check

Unfortunately, popular current BIM authoring tools do not natively support such feature and achieving this behaviour would require development of an add-on. For software tools that offer an Application Programming Interface (API) this would be possible. This solution could rely on an internal data structure or on an external file for keeping these data or even on saving them along with standard content in the application's native file, depending on the available programming features. Revit's API (Autodesk Inc, n.d.), for example, allows storing multiple schemed data into model's components. This enables a plugin to manage each component instance linking them to a local database for recording the status of all its properties.

Another approach is to maintain a side database, relating each component's GUIDs, its properties and current status. As shown in Figure 3, an external database would keep a list of properties of each object instance in the BIM model, along with their status (asseverated or not).

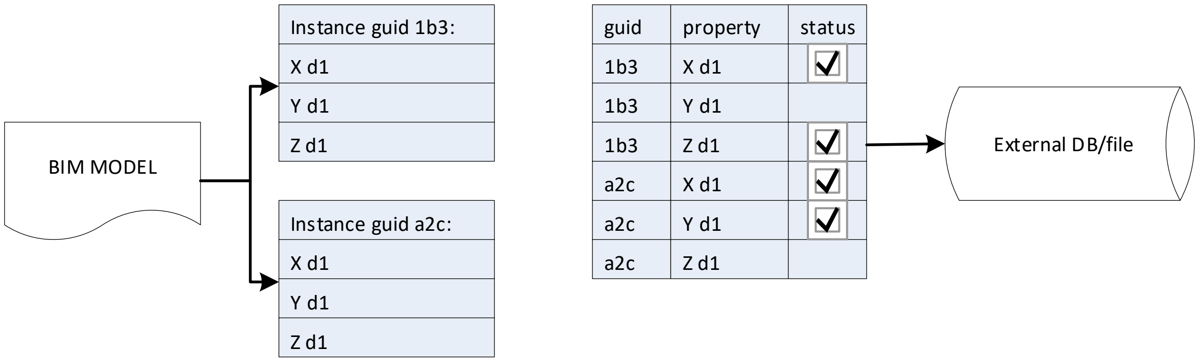


Figure 3: Component attribute status mapping to an external database

Creating such plugin would be challenging or even impossible due to the lack of a development interface (public API for developers) in some authoring tools. In such situations, an external software (fully independent from the authoring application) could perform a similar task based on an interoperable format (e.g. IFC, Industry Foundation Classes) exported from the modelling software.

The advantage of building such tool is that it could work with any IFC-compliant soft vendor acting as a post-processor for the model helping author to find unverified or missing requirements. Since components' GUID don't change for each exportation, items already verified can be easily identified, avoiding re-work, making necessary only the verification of new requirements since the prior milestone.

3.2 Digitized MET requirements

The previous proposal relies on a mixed use of technologies (plugins) for supporting the asseveration procedure and is still based on human-focused documentation (MET on BEP), which leads to time-consuming and error prone procedures.

Enabling machine interaction with such documentation is desirable and could be achieved in many ways. Application Programming Interfaces (APIs) for reading spreadsheet files (e.g. .xlsx files) are widely supported and accessible for developers. Having those documents formatted in such way that computer programs can read them makes it possible for authoring tools to access project planning and requirements.

More sophisticated solutions are already being offered to allow BIM managers and other project stakeholders collaborate on creating the projects requirements. That's the case of LOD Planner (Planner, 2019), an online web-based tool that helps the construction of the project scope and BEP with a user-friendly interface. If projects like this evolve to enable internet access to its information (through a REST API, for example), developers could build solutions that enable, for example, authoring applications to access project requirements for next delivery milestone and compare them with the current status of models being developed.

That feature can both help model developers on the task of assuring the delivery is in accordance with the MET requirements and also support information consumers on identifying valid information in the model.

Although these tools help in both ends (model creation and information consuming), it is noteworthy to remember that the reliability of information is still implicit. The consumer assumes the model delivered to one milestone had all information verified through the asseveration procedure, but there is no explicit tagging on each model's component to guarantee it.

3.3 CDE-Integrated solution

One way of filling all the gaps and solving possible doubts and uncertainties along the process would be to store all project information (BEP, MET, model content, etc.) in a single data repository. That is the reason for implementing and integrating the procedure of model asseveration onto a CDE (Common Data Environment). Instead of an external database for each model (as described for the first approach), a single database for all models of the project would hold the verification register for each piece of modelled data.

Enabling the access to this data via internet (REST API), by authenticated and authorized users, could enable a much more flexible project planning and development.

Using the CDE as a model server and MET keeper would allow features like filtering unchecked information so that it does not appear for information consumers (both on online model viewers and in model file downloading, in which case the interoperability file could have unverified data removed during exportation), as represented on Fig. 4. That way, all the information accessed by consumers through the CDE is considered explicitly asseverated and reliable for consumption.

This approach enables many other related features for supporting the asseveration procedure that will be explored in future works.

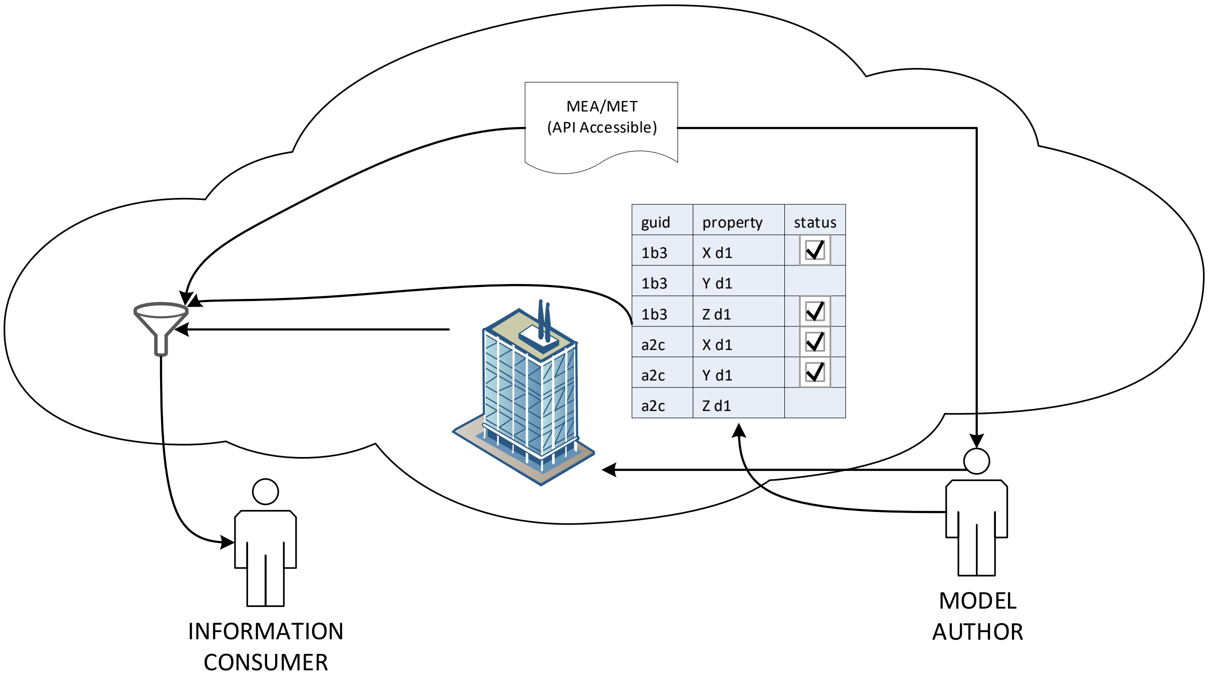


Figure 4: CDE-enabled asseveration procedure schema

3.4 Normative approach

Faria & Santos (2018) developed a prototype tool for automating the creation of a MET from a table-formatted input consisting on intended BIM uses vs. project milestones. This tool is based on a database that relates information requirements to BIM uses at standard project phases. This same database could be used to support asseveration without the need to access online MET information, as long as the information on this database is standardized. The use of such a standard would dismiss the need for a MET, which could be replaced by a much simpler MUxPM (Model Uses x Project Milestones) Table.

These standardized attribute lists for each BIM use could be pre-loaded on authoring software, a CDE or complementary programs to aid the designer on producing and asseverating a BIM model. Those systems would be able to asseverate the model contents against intended BIM uses.

The Brazilian Association of Technical Standards (ABNT – *Associação Brasileira de Normas Técnicas*), is developing a related standard on their ABNT/CEE-134 BIM Objects WG ("Requirements for Building Information Modelling (BIM) Objects" standard under development). This standard establishes the requirements on BIM object content (geometry level of detail, properties, connectors, 2D representations) based on intended Model Uses (e.g., Energy Analysis, 4D Planning, Quantity take-off, Electrical Building System Design, etc.).

One possible downside of such strategy is the low flexibility of such rigid documentation as standards, that usually takes years to be revised/updated – what would lead to slow response time for improvements and new BIM uses. But this work could be the foundation for a customizable solution, with flexible capabilities.

An extra parameter would be inserted on each object instance informing the BIM uses that component is ready for (this is required in the mentioned Brazilian standard). As long as new information is inserted, other uses would be enabled and this attribute updated– this could be automated on an authoring tool using a plugin.

4. Conclusions

Anecdotal evidence shows most BIM professionals do not use the recommended practice of verifying the validity of required data in their authored models against a project-defined Model Element

Table at each delivery milestone nor they check the same table for confirming the validity of other's model data before consumption. These two rarely performed procedures do not have a defined name, as evidenced on performed literature review. In this work, we proposed to name the act of "*asserting the validity of all required model information (including both geometry and properties)"* as "asseveration". We hope that having a name for it will help to foster awareness about it and stimulate the development of supporting tools, increasing its adoption and practice.

Current BIM authoring tools and CDE platforms do not offer support for asseveration. In this work we proposed several approaches that can be used on computer tools for aiding asseveration of models. Two proposed approaches are client-side: i. storing asseveration flags inside the model, on the authoring tool, and; ii. storing asseveration status on an external database, created from the model data through a plugin. Another proposed solution is implemented on both client and server sides: storing MET information on the server to allow client queries on what information needs to be asseverated (author side) and filtering out information that cannot be consumed (consumer side). A fourth solution is to implement a server-side only approach, where both MET data and models are kept on a Common Data Environment. Both properties asseveration and filtering would be performed at this specialized server. An alternative approach, useful on all proposed solutions, replaces the MET table with a Model Uses x Project Milestones Table and a Model Uses x Properties database, although this database is pending development yet.

The tools proposed in this paper can both help the designer asseverate models before delivery and also the model information consumers, by assuring that only validated data is exchanged reliably.

The next step in our research is to implement the most promising approaches and validate them on a real scenario project (study case), measuring its performance, benefits and the perception of the users.

References

Abualdenien, J., & Borrmann, A. (2019). A meta-model approach for formal specification and consistent management of multi-LOD building models. *Advanced Engineering Informatics*, *40*(March), 135–153. https://doi.org/10.1016/j.aei.2019.04.003

Archistar (2019). A Comparison between CAD and BIM. [Blog post]. Retrieved from https://academy.archistar.ai/a-comparison-between-cad-and-bim

Autodesk Inc. (n.d.). Extensible Storage. Retrieved May 5, 2019, from http://help.autodesk.com/view/RVT/2018/ENU/?guid=Revit_API_Revit_API_Developers_Guide_Advanced_Topics_Storing_Data_in_the_Revit_model_Extensible_Storage_html

BSI (2013) Specification for information management for the capital/delivery phase of construction projects using building information modelling. PAS 1192-2:2013. London, UK: BSI Group.

Dresch, A., Lacerda, D. P., & Antunes, J. A. V. (2014). Design Science Research: A Method for Science and Technology Advancement. Springer Publishing Company, Incorporated.

Faria, D. R. G., & Santos, E. T. (2018). A Tool for Automating BIM Model Elements Table Creation from Intended BIM Uses and Milestones. In: 17th International Conference on Computing in Civil and Building Engineering. Proceedings of ICCCBE 2018, Tampere, Finland, 5-7 June 2018, p. 58-65. Retrieved from http://programme.exordo.com/icccbe2018/delegates/presentation/378/

Kassem, M., & Succar, B. (2017). Macro BIM adoption: Comparative market analysis. Automation in Construction, 81, 286-299.

LOD Planner. (n.d.). Online BIM Execution Planning Software. Retrieved May 5, 2019, from https://www.lodplanner.com/product/

Migilinskas, D., Popov, V., Juocevicius, V., & Ustinovichius, L. (2013). The benefits, obstacles and problems of practical BIM implementation. Procedia Engineering, 57, 767-774.

Oliveira, F. M., & Santos, E. T. (2019) Asseveração de modelos BIM: conceituação e terminologia. In: Simpósio Brasileiro de Tecnologia da Informação e Comunicação na Construção, Proceedings of II SBTIC, 19-21 August 2019, Campinas, Brazil.

Reinhardt, J., & Bedrick, J. (2019), *LOD Spec 2019 Guide and Commentary*, BIMForum, Retrieved from https://bimforum.org/wp-content/uploads/2019/04/LOD-Spec-2019-Part-I-and-Guide-2019-04-29.pdf

Sacks, R., Gurevich, U., & Shrestha, P. (2016). A review of building information modeling protocols, guides and standards for large construction clients. Journal of Information Technology in Construction (ITcon), 21(29), 479-503.

Challenges in Energy Analysis of BIM based Building Projects During Early Design Phase

Zaid Alwan[1], Amalka Nawarathna[2*] and Rana Ayman
[1,2,3]Northumbria University, Newcastle Upon Tyne, UK
* email: amalka.ranathungage@northumbria.ac.uk

Abstract

The challenges presented by excessive energy use in the built environment have been well documented and proven by many academic and national research over the past 20 years. These are mainly manifested in climate change direct and indirect impacts on health and well-being, as well as irreversible damage caused on a global scale. As a consequence, a variety of physical and voluntary approaches have been taken at international levels to limit the impacts caused. However, the problems associated with the built environment is quite complex as energy consumption and carbon emission of buildings have been increasing for several decades.

Effective reduction in energy consumption within the AEC (Architecture Engineering and Construction) sector needs a detailed understanding of where energy is used, and carbon associated with it on a building. With the advancement of Building Information Modelling (BIM) applications in AEC sector, integration of building energy analysis with BIM has received much interest of researchers and governments at present. As a result, number of researches have been conducted in order to integrate Life cycle energy analysis with BIM. However, what has lagged behind is the effective integration of whole life cycle energy analysis and applying digital analysis prediction of energy consumption as a tool within BIM frameworks.

Therefore, this paper attempted to investigate the challenges and difficulties faced in using existing life cycle energy analysis tools during early design phase of BIM based projects. The findings revealed that complexity and time-consuming nature of mapping life cycle input data, interoperability with BIM and determining an adequate granularity and development process for building BIM model as key challenges. Accordingly, the study suggests the necessity of an effective, accurate and complete energy analysis tool which can be integrated into BIM based projects during their early design phase.

Keywords: Building Energy Modelling, Life Cycle Energy Analysis, Early Design Stage

1. Introduction

The building sector is considered as a major energy consumer as well as a major culprit for the increasing presence of atmospheric carbon. In the UK, almost 40% of energy consumption and carbon emissions come from the operation of buildings (MHCLG, 2014). Therefore, awareness on optimizing of energy consumption and carbon reduction in buildings has been increased over the last years, making the energy performance of buildings legislation (England and Wales) more stringent. As explained by MHCLG (2014), even small changes in energy performance and the way each building is occupied will have a significant effect in reducing total energy consumption.

A building within its lifetime consumes not only the operational energy but also the embodied energy. Operational energy is the energy required to run a building by operating processes such as heating and cooling, lighting, ventilating and appliances; whereas embodied energy of a building is the energy consumed by all the processes associated with its production i.e. extract raw resources, process materials, assemble product components, transport between each step, construction, maintenance and repair, deconstruction and disposal (Ibn-Mohammed et al., 2013). Therefore, optimization of energy consumption of buildings requires equal attention on both operational and embodied energy.

Building energy analysis is the main drive towards energy optimization. It enables a deeper understanding of the likely effects of the changes in building design and occupation which affect the energy performance of buildings (BRE, n.d). An energy analysis can be performed during building design, construction, and/or operation stage. However, according to the Energy Performance of Buildings Regulation (2012), it emphasizes that energy modelling should be carried out at an early stage of the design process of new buildings in which more opportunities are available to optimize the energy consumption by further improving the design and construction.

During the last decade, Building Information Modelling (BIM) had significant growth within Architecture, Engineering and Construction (AEC) industry enabling to improve decision making and performance across the building and infrastructure lifecycle (Gokuc and Arditi, 2017). Incorporating energy analysis into BIM during design stage would certainly provide many benefits including giving more room to create alternative options which optimize the whole building life cycle energy consumption. Number of researches have been carried out integrating embodied and operational energy assessment with BIM in isolation platforms, but limited research contributions were found integrating whole building life cycle energy analysis (operational and embodied) with BIM during early design stage to optimize the total energy consumption (Shadram and Mukkavaara, 2018). Accordingly, this study explores the challenges in using existing tools for whole buildings life cycle energy analysis during early design phase of BIM based projects.

This paper is organized into six main sections; section 1 briefly introduces the aim of this study, section 2 presents the methods adopted to conduct the study, this is followed by benefits of BIM based energy analysis during early design stage of buildings are discussed under under Section 3, section 4 explains existing building energy analysis tools. The challenges in using existing tools for energy analysis during early design phase of BIM based projects are discussed in section 5. In the end, the section 6 draws the conclusions and future work.

2. Method

The purpose of this paper was to investigate the challenges in using existing LCEA(life cycle energy analysis) tools during design phase of BIM based projects. Accordingly, the paper followed a systematic literature review. The search results limited to last 10 years period and thus, related books, journal articles, government publications, web sites, newspaper articles, and other published reports were referred.

3. Benefits of Energy Analysis of BIM based Buildings During Early Design Stage

In the building industry, the concept of BIM has gained increasing acceptance over the last years, increasing collaboration among building design and construction project members (Eastman et al, 2011; Schlueter and Thesseling, 2009). According to the US National Institute of Building Sciences Facilities Information Council (2010), "BIM is a digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition".

In the traditional project delivery method, the work of architects, structural engineers, MEP engineers, contractors, and various other building consultants occurs in relative isolation to one another. However, BIM-based project delivery method, information available to the various parties can all be shared and integrated around a central building information model (Azhar, et.al., 2011). In addition, immersive virtual environments (IVEs) combine pre-construction mock-up that presents a sense of real space to the future users and building information models that allow for testing of different design alternatives (Heydarian et al., 2015).

In conventional energy modelling approach, traditionally created 2D drawings were used to create an independent model in an energy modelling tool (US GSA, 2015). This may lead to misinterpretation of the drawings, inconsistencies, simplified model, and large amount of time needed to create an energy model (Reeves, Olbina and Issa, 2015). In contrast, BIM-based energy analysis assists to automate this process and create consistent and more complex energy models which provide faster and accurate results compared to the traditional methods (Azhar et.al., 2011; US GSA, 2015). In BIM-based project delivery, energy analysis can be integrated into building design, construction, and operation/maintenance more efficiently as energy performance is analyzed using the central BIM model without having to recreate building geometry in certain energy analysis platforms (i.e., gbXML-enabled tools). According to US-GSA (2015), use of BIM -based energy analysis provides several benefits including: more accurate and complete energy performance analysis in early design stages, improved lifecycle cost analysis, and more opportunities for monitoring actual building performance during the operation phase. In addition to them, it will assist to assess the energy benefits of various design alternatives and thus help designers and owners make better decisions related to materials and products selection that have low environmental impact (Donn, Selkowitz and Bordass, 2012).

4. Existing Building Energy Analysis Tools

Most of the important decisions related to energy efficiency are made early in the design process as more energy savings can be achieved later on in the project (Cemesova, et al., 2015). And importantly, Energy performance regulation (2012) mentions that energy modelling should be carried out at an early stage of the design process of new buildings, in order to inform further development of the design and construction. As a result, number of tools have been developed to support the operational and embodied energy estimation and analysis process. The below two sections describe such existing operational and life cycle energy analysis tools.

4.1 Operational energy analysis tools

Operational energy analysis is an assessment of the overall building energy performance (BEP) and also known as building energy modelling (BEM). There are various existing BEM tools available for the use of architect and building services engineers in order to evaluate the design decision during the preconstruction design stages in informing building design performance analysis and validation (Hyun, Marjanovic-Halburd and Raslan, 2015). These tools can be used during conceptual and early design stage in order to:

1. Understand climate and weather of the project location
2. Inform the massing and orientation phase
3. Design and selection of materials for building fabric
4. Simulate the energy use of building services (Zanni, 2016 and Reeves, Olbina and Issa, 2015)

Table 1 summarises the existing BEM tools that can be used to above purposes during early design stage of a building development.

Table 1: Operational Energy Analysis Tools

Purpose	Design/ Energy variables	BEM tools
Climate and weather	Daylight availability Solar access/intensity Wind direction/intensity Temperature range Humidity	Autodesk Vasari Sefaira Autodesk Revit PHPP IES-VE EcoDesigner EDSL TAS Bentley Hevacomp TRNSYS

		Climate consultant
Massing and orientation	Overshadowing Building height and footprint Irradiance over building's planes Thermal performance Daylight Ventilation	Sefaira Autodesk Revit plug in IES-VE EnergyPlus eQuest PHPP iSBEM
Building fabric	Glazing and shading Daylighting Insulation properties of building skin: Solid and voids (U-Values and G-values) Airtightness (at 50 Pa) Ventilation and free cooling Overheating	IES-VE Sefaira EnergyPlus (engine) PHPP DesignBuilder (operated by energy plus) Open studio (operated by energy plus) EcoDesigner EDSL TAS Bentley Hevacomp TRNSYS EnergyPlus
Building services	Energy consumption Heating, cooling, and hot water Electric load IT and small power consumption Energy source Artificial lighting Occupation schedules	IES-VE Bentley Hevacomp Modelica Sefaira EnergyPlus (engine) DesignBuilder EcoDesigner EDSL TAS TRNSYS Assessment (SWERA) Solar Deployment System (SolarDS) Open studio (operated by energy plus)

Source: Zanni, 2016 and Reeves, Olbina and Issa, 2015

In the UK , only few tools such as IES-VE, DesignBuilder and EnergyPlus engine are approved and compliant for the high accuracy as they are accredited by UK's National calculation method (NCM) (BRE, no date). But, still the use of those tools are reported to be non-user friendly specially for architects, too complex and require high detailed input, beside it is not compatible to the architects' iterative working need for exploring multiple alternatives at early stage that requires manageable input (Arayici et al., 2018).

4.2 Life cycle energy analysis tools including embodied energy

Numerous studies in the last ten years have been conducted for general BIM-LCA integration and estimation of embodied energy in particular. Table 2 presents few such tools which can be used to estimate life cycle energy including embodied energy during early design stage of a building. The required input and system boundaries of each tools are also summarised in the table.

Table 2: Life Cycle Energy Analysis Tools

Tool	Input required	System boundary and region of database
Tally (Kieran Timberlake, 2014)	**Automatic Quantity take-off from model:** Only required to assign the unit of material calculation/ Material take off options (Length, area, volume) **Automated family identification:** All objects are automatically available in the interface according to modelled families. **Required material mapping:** Required the material mapping of the existing materials to the material library database in the program.	**Allow cradle to grave system boundary.** Usually user rely on industry average transportation and construction impact. Ignores construction details and asks for lump sum value. -Material database used is German database GABi and filtered to North America market and manufacturers.
One Click LCA (One Click LCA, n.d)	**Import open standard BIM schema file either IFC or gbxml and file additional project information.** Similar to tally.	**Allow cradle to grave system boundary.** -complies with European standards and has template for North American Market as well -Have different schemes for use in UK and international schemes as well
Athena Impact Estimator (Bowick, O 'connor and Meil, 2010)	- **manual entry of project material take-off** - **Assembly information** (geometry, assembly/material choice, loading) - **Operational energy information** (annual operating energy) - **Building information** (location, life expectancy, occupancy type, floor area, height)	High detailed tool with high range of LCA scoping according to: 1. Object of assessment eg. Core and shell 2. System boundary, Life cycle activities To according include scenario for database Suitable for Canadian and US regions.
etool LCD (Hermon and Higgins, 2015)	Similar to Athena IE	Similar to Athena IE, but have different schemes for use in the UK and international European and US schemes as well

Ms Excel and data base such as ICE, Gabie, US LCI	-Manual entry of material quantities that can be -Manual search through data base to get coefficients of the embodied energy values for excel calculations.	**Flexible method** as User can determine the system boundary. Level of complexity is also determined by the user.

5. Challenges in Using Existing Tools for Whole Life Cycle Energy Analysis of BIM based Projects During Early Design Phase

BIM facilitates energy efficient design within the energy consumption assessment throughout the entire life cycle of buildings (Häkkinen and Kiviniemi,2008). However, there are many challenges in using tools mentioned in Table 2 for assessing whole life cycle energy during early design stage of BIM based projects due to lack of interoperability of existing tools, lack of input data during early design stage and difficulty in determining an adequate granularity and development process for building BIM models.

5.1 Complexity and Time-Consuming Nature of Mapping Life Cycle Input Data

The complexity and time-consuming nature of mapping the life cycle input data with building material quantities is one of the main challenges confronted using existing tools (Soust-Verdaguer, Llatas and García-Martínez, 2017). The multiple manual input required to match the sustainability data with the material properties database question the practicality of use due to the need for long modelling time and high susceptibility in errors during transfer. A study done by Jarde and Abdulla, 2012, accessed the embodied energy and carbon for two different alternatives of houses, the first is mud-brick and second is cement block. The manual calculation presented in the study to estimate the embodied energy and carbon for two alternatives reflects the complexity and time consumption required to compare results, which highly affect the uptake of this approach by architects in early design.

5.2 Interoperability of existing tools with BIM

The other challenge is the lack of interoperability between BIM model and LCA tools which limited the role of BIM model. Table 3 summarises the interoperability with BIM and complexity of life cycle energy analysis tools identified in Table 2.

Table 3: Interoperability and complexity of existing Life Cycle Energy Analysis Tools

Tool	Interoperability with BIM environment and complexity
Within BIM Environment	
Tally (Kieran Timberlake, 2014)	**Plugin limited only for Revit** - It is plug in within Revit architecture or structure model - Depends on the granularity and detail of BIM model LOD **Deal with 3 detailed levels:** - Schematic design: showing building components weighting

	- Design option comparison: comparing reports but the after mapping of materials once and executing the results report are available in the BIM model - Complete LCA **Closed commercial product:** Limited customized development or update for the inventory data and not flexible to other system boundaries.
One Click LCA (One Click LCA, n.d)	**Can be used with wide range of software not limited to one** - Web based interface software (IFC can be plugin in Revit, IES-VE, Graphisoft ArchiCAD, tekla structures etc.)
On separate platform- BIM model can just be used for material take-off	
Athena Impact Estimator (Bowick, O 'connor and Meil, 2010)	- Manual entry of material quantity information and required high experienced LCA individual to complete information module about product, construction installation, use, end of life. - Very complicated for the use of screening and simplified LCA that is suitable for early design conceptual phases
etoolLCD (Hermon and Higgins, 2015)	- Manual entry of all Material, Assembly and operational inputs - Have simplified scheme
Ms Excel and data base such as ICE, Gabie, US LCI	- Results are not connected to the BIM model - Level of complexity is flexible and can be designed to suite the conceptual design stage - High possibility of errors - Doesn't allow iterative process as it will be impractical and time consuming - Reliability is not assured and validation is required

5.3 Determining an adequate granularity and development process for building BIM model

The third challenge is determining an adequate granularity and development process for building BIM model. Lee et al., 2015 proposed a framework for automated LCA within BIM model without data exchange. This framework utilizes the use of parametric modelling and inter-object data relationship which associate embedded impact factors of the materials in Revit family (∗. rfa) file. After preparing Revit family for each building element by using a family writer tool, the file is used by the modeller in the BIM authoring tool (Revit). This requires a development of model of LOD 300 or higher in addition to the need for high skilled modeller to use the developed built in family. Another effort in automating calculation of LCA impact factors without exchange of data is proposed by Jrade and Jalaei, 2013. Similar to Lee et al., 2015, the provided framework which adds unique keynote i.e. parameter in each Revit material family. Manual preparation of the material library is required before use by filling keynotes for the plenty potential materials. Despite, these studies provided automatic calculation within BIM environment with no exchange of files between different platforms, the method provide complex and impractical use in the industry current state. This is reasoned by the current lack of ready to use material library and requirement for high skilled modeller of the use of detailed built-in family.

6. Conclusions and Future Work

The finding of the systematic and mapping analysis of available methods in energy analysis tools, reveals that while tools do exist for sustainability purposes, they are currently standalone and not fully compatible with existing BIM frameworks. In order for the construction industry to fully utilize benefits of energy and carbon predictions at early stages in a project, and allow for different options in terms of material selections in order to make more informed decisions in relations to life cycle analysis, more needs to be done on a technical and operational levels. The research for this paper has highlighted that while ready off the shelf tools exist, they are limited by commercial and technical boundaries making them unacceptable to most design and construction professional and attractive only to sustainable minded developers and clients. The main outcomes and conclusions can be summarized as follows:

- Greater collaboration and input are needed amongst stakeholders adopting BIM strategies and development of bottom up approaches to appreciate the importance of energy and carbon within developments.
- Early support and predication are key to achieving energy targets and thus CO2 reductions. The Climate Change Act (2008) also pushes for tough measures, establishing that the UK must reduce emissions by 80% from 1990 levels by 2050. If BIM has been proposed as policy for change and efficiency it must incorporate energy elements and targets.
- LCA and energy predication can be linked to long term Facilities Management (FM), so making a case for energy analysis at earlier stages set the agenda for long term carbon strategy

This is early phase of a work funded by the Centre for Digital Built Britain (CDBB) and fits into its Agenda of "A digitally enabled built environment will transform the way we live, play and work"

Suggestions for future work which are part of the study is to produce a definitive methodology for evaluating the life-cycle of buildings through the lens of BIM and whole energy and carbon emissions The outputs of this research will assist government, developers and planners to compare and contrast options at early design phases.

Acknowledgements

The authors wish to acknowledge the support by the CDBB (Centre for Digital Built Britain), (https://www.cdbb.cam.ac.uk/) early career research scheme project reference DEET (Digital Energy Estimation Tool). The Centre's mission is to develop and demonstrate policy and practical insights that will enable the exploitation of new and emerging technologies, data and analytics to enhance the natural and built environment.

References

Arayici, Y., Fernando, T., Munoz,V., & Bassanino, M. (2018). Interoperability specification development for integrated BIM use in performance based design, *Automation in Construction*. *85*(2018), 167-181. http://dx.doi.org/10.1016/j.autcon.2017.10.018

Azhar, S., Carlton, W.A., Olsen, D., & Ahmad, I. Building information modelling for sustainable design and LEED rating analysis. *Automation Construction. 20*(2011), 217–224. doi:10.1016/j.autcon.2010.09.019

Azari, R., & Abbasabadi, N. (2018) Embodied energy of buildings: A review of data, methods, challenges, and research trends, *Energy and Buildings*. *168*, 225–235. doi: 10.1016/j.enbuild.2018.03.003.

Bowick, M., O 'connor, J., & Meil, J. (2014) *Athena Guide to Whole--Building LCA in Green Building Programs*, 1st ed. Retrieved from https://calculatelca.com/wp-content/uploads/2014/03/Athena_Guide_to_Whole-Building_LCA_in_Green_Building_Programs_March-2014.pdf

BRE. (n.d). *UK NCM*. Retrieved from: http://www.uk-ncm.org.uk/.

Cemesova, A., Hopfe, C., and Mcleod, R. PassivBIM: Enhancing interoperability between BIM and low energy design software, *Automation Construction*. *57*, 17–32.

Cavalliere, C., Habert, G., Dell'Osso, G.R., & Hollberg, A. (2019). Continuous BIM-based assessment of embodied environmental impacts throughout the design process, *Journal of Cleaner Production*. *211*, 941–952. doi: 10.1016/j.jclepro.2018.11.247.

Donn, M., Selkowitz, S., & Bordass, B. (2012) The building performance sketch. *Building Research and Information. 40,* 186–208. https://doi.org/10.1080/09613218.2012.655070.

Eastman, C.M., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*, 2nd ed. Hoboken, NJ, USA: John Wiley and Sons, Inc.

Energy Performance of Buildings Regulation (2012) Retrieved from: http://www.legislation.gov.uk/uksi/2012/3118/contents/made

Eon, C., Murphy, L., Byrne,J., & Anda, M. (2017) Verification of an emerging LCA design tool through real life performance monitoring, *Renewable Energy and Environmental Sustainability*. *2* (26). doi: https://doi.org/10.1051/rees/2017017.

Häkkinen, T., & Kiviniemi, A. (2008). Sustainable building and BIM, *In* Proceedings of the conference on sustainable Building SB08 Melbourne, 21-25 September 2018.

Hermon, P. and Higgins, J. (2015) *Life Cycle Assessment:International Residential Benchmark*. Retrieved from: https://etoolglobal.com/wp-content/uploads/2015/06/International-Residential-Benchmark-Weighted-x10-dwellings-v28.pdf

Heydarian, A., Carneiro, J.P., Gerber, D., Becerik-Gerber, B., Hayes, T., & Wood, W. (2015). Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations. *Automation in Construction. 54*, 116–126.

Hyun, S., Marjanovic-Halburd, L., & Raslan, R. (2015). Investigation into informational compatibility of Building Information Modelling and Building Performance Analysis software solutions. *WIT Transactions on The Built Environment. 149,* doi: 10.2495/BIM150441.

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings- a review of current trends, *Energy and Buildings. 66* (2013) 232–245, doi: 10.1016/j.enbuild.2013.07.026.

Jarde, A. and Abdulla, R. (2012) Integrating Building Information Modeling and life cycle assessment tools to design, in *Proceedings of the CIB W78 2012: 29th International Conference –Beirut, Lebanon, 17-19 October*, pp. 17–19.

Jrade, A., and Jalaei, F. (2013) Integrating building information modelling with sustainability to design building projects at the conceptual stage, *Building Simulation*. *6*(4), 429–444. doi: 10.1007/s12273-013-0120-0.

Kamel, E., and Memari, A. M. (2018) Automated building energy modeling and assessment tool (ABEMAT), *Energy*. *147*, 15–24. doi: 10.1016/j.energy.2018.01.023.

Timberlake, K. (2014) Tally, Retrived from:https://choosetally.com/.

Köseci, F. C. (2018) *Integrated life cycle assessment (LCA) to building information modelling (BIM)* (Master's Thesis). Retrieved from: http://www.diva-portal.org/smash/get/diva2:1229841/FULLTEXT01.pdf

Lee, S., Tae, S., Ro, S., & Kim, T. (2015) Green template for life cycle assessment of buildings based on building information modeling: Focus on embodied environmental impact, *Sustainability (Switzerland)*, *7*(12), 16498–16512. doi: 10.3390/su71215830.

MHCLG, (2014). *Guidance Energy Performance of Buildings Certificates: notes and definitions.* Retrieved from: https://www.gov.uk/guidance/energy-performance-of-buildings-certificates-notes-and-definitions

NBIMS. The US National Institute of Building Sciences Facilities Information Council, B. C. (2010) *National BIM Standard-United States,*

Nizam, R. S., Zhang, C., and Tian, L. (2018). A BIM based tool for assessing embodied energy for buildings, *Energy and Buildings*. *170*, 1–14. doi: 10.1016/j.enbuild.2018.03.067.

Noack, F., Katranuschkov, P., Scherer, R., Dimitrious, V., Firth, S.K., Hassan, T.M., Ramos, N., Pereira, P., Malo, P., & Fernando, T. (2016) Technical challenges and approaches to transfer building information models to building energy, in *eBusiness in Architecture, Engineering and Construction: ECPPM 2016: Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2016), Limassol, Cyprus, 7-9 September 2016*, p. 355.

One Click LCA (n.d), Retrived from: https://www.oneclicklca.com/'.

Peng, C. (2016). Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling, *Journal of Cleaner Production*, *112,* 453–465. doi: 10.1016/j.jclepro.2015.08.078.

Reeves, T., Olbina, S. and Issa, R. (2015). Guidelines for Using Building Information Modeling for Energy Analysis of Buildings, *Buildings*, *5*(4), 1361–1388. doi: 10.3390/buildings5041361.

Schlueter, A and Thesseling, F. (2009). Building information model based energy/exergy performance assessment in early design stages, *Automation in Construction. 18* (2009) 153–163 doi :10.1016/j.autcon.2008.07.003

Shadram, F., Johansson, T.D., Lu, W., Schade, J., & Olofsson, T., (2016). An integrated BIM-based framework for minimizing embodied energy during building design, *Energy and Buildings*, 128, 592–604. doi: 10.1016/j.enbuild.2016.07.007.

Shadram, F., and Mukkavaara, J. (2018). An integrated BIM-based framework for the optimization of the trade-off between embodied and operational energy, *Energy and Buildings*, 158, 1189–1205. doi: 10.1016/j.enbuild.2017.11.017.

Tulubas Gokuc, Y. and Arditi, D. (2017). Adoption of BIM in architectural design firms', *Architectural Science Review*, *60*(6), 483–492. doi: 10.1080/00038628.2017.1383228.

UK Green Building Council, 2017. Delivering Low Carbon Infrastructure.

U.S. General Services Administration (US GSA). (2015) GSA BIM Guide 05- Energy Performance. Version 2.1. Retrieved from: http://www.gsa.gov/portal/mediaId/227119/fileName/GSA_BIM_Guide_ 05_Version_21.action

Yang, X., Hu, M., Wu, J., & Zhao, B.(2018). Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China, *Journal of Cleaner Production*. *183*, 729–743. doi: 10.1016/j.jclepro.2018.02.070.

Zanni, M. A. (2016) *Communication of sustainability information and assessment within BIM-enabled* *collaborative environment* (Doctoral Thesis) doi: 10.1021/ja00090a013.

Zanni, M. A., Soetanto, R. and Ruikar, K. (2013). Exploring the potential of BIM-integrated sustainability assessment in AEC, IN: Soetanto, R. (ed.) *Proceedings of the Sustainable Building and Construction Conference (SB13)*. Coventry, 3-5 July 2013, PP 186-195.

The influence of managerial strategy on the implementation of BIM in facilities management: a case study

Saratu Terreno[1,*], Ruwini Edirisinghe[2], Chimay Anumba[3]
[1] Pennsylvania State University
[2] Royal Melbourne Institute of Technology
[3] University of Florida
[*]email: snt120@psu.edu

Abstract

The implementation of Building Information Modeling (BIM) in lifecycle management can positively impact the performance of Facilities Management (FM) operations. However, the adoption of BIM in FM has been slow due to a lack of sufficient know-how in implementation. This study aims to explore the drivers and challenges for BIM adoption in FM in a showcase organization, with a particular emphasis on managerial strategy including the influence of policy. A case study that illustrates the journey of a tertiary institution, which is an early adopter of BIM, is presented. It details the interviews conducted with the upper and mid-level institutional representatives, and reviews of BIM-related documentation. Aspects of managerial approach are analyzed, including their motivation, organizational policy, choice of BIM uses and requirements, procurement planning, adoption strategies and technological impact. It was found that the top-down approach of managerial strategy has greatly influenced the sustainability and success of the BIM process downstream. The paper concludes with an evaluation of lessons learnt following an analysis of the recorded experiences. The documentation of these experiences will provide a needed source of information and lessons illuminating skill sets, decision styles and strategies for organizations planning to implement BIM in FM.

Keywords: Building Information Modelling, Facilities Management, Strategy, Policy.

1. Introduction

BIM is a major transformative influence with the potential to improve the efficiency of multiple FM processes (Becerik-Gerber et al. 2012, Teicholz, 2013, Eastman et al. 2011), with FM in turn having been shown to possess huge potential for enhancement of organisational and societal well-being (Amaratunga, 2000). Although the delivery of the value of BIM in construction has been focused on how to improve the product, the value of BIM in FM has instead been focused on how to prove the product. A gap in knowledge as expressed by facility managers in relation to BIM includes the need for more examples of demonstrated benefits of the integration, and increased abilities in the utilization of BIM deliverables (McGraw Hill, 2014). Kiviniemi & Codinhoto (2014) concluded that the integration of BIM and FM is hardly straightforward, with numerous missing links and intricacies. They advocated for an FM-BIM 'Champion/Expert' for the facilitation of a smoother transition; and observed that the main challenges in integration are more attributable to current work procedures and organisational structures. Munir & Jeffrey (2012) determined that the real value of a BIM asset can never be clear-cut owing to a collection of variables as evident in an organization's established disposition, amongst others.

Studies have illustrated the slow adoption of BIM in FM by owners (McGraw Hill, 2014; Kiviniemi & Codinhoto, 2014), and also highlighted the knowledge gap on the part of the FM professionals (Liu & Issa, 2013; Williams et al., 2014).

Thus, there is a need to address this hesitancy by providing real-life examples of implementation to fill in the learning gap. Studies examining the organisational dynamics of BIM adoption in FM are lacking, though this is an essential part of technology diffusion in practice. The aim of this study is to address the obvious knowledge gap by examining the organisational dynamics of BIM implementation in FM by an early adopter. It is part of a doctoral research project at the Pennsylvania State University that examines a wide range of organizations to uncover influential factors in the value delivery of BIM in FM.

1.1 BIM in FM infancy

It has been argued that BIM-enabled FM is able to solve many problems faced in traditional FM practice (Teicholz, 2013). The usefulness of digital modelling for asset management, particularly in operations and maintenance, has been widely explored in literature. For over half a decade, researchers (Eastman et al., 2011; Becerik-Gerber et al. 2012; Volk et al., 2014; Kassem et al. 2015; Yalcinkaya and Singh, 2015; Shen et al., 2016; Edirisinghe et al, 2016) have discussed value propositions and driving forces for BIM-enabled FM.

Value propositions for BIM-enabled FM have reported on operational efficiencies, productivity, quality of service improvements, and on organisational goals and mission aspects. Operational efficiencies are to be achieved through accurate FM data (Kassem et al., 2015), and increased efficiency in building commissioning (Eastman et al. 2011), work orders, and decision making (Yalcinkaya and Singh, 2015). Productivity improvements are realised through automated data population, real-time data access (Becerik-Gerber et al., 2012), and BIM serving as the single source of information (Edirisinghe et al, 2016) in contrast to the large number of software packages.

Studies have reported that FM accounts for up to 85% of lifecycle costs (Teicholz, 2004), and is five to seven times more costly than the initial investment (Lee et al., 2012). Regardless of the precise proportions (BIM Task Group, 2012), the on-going operation and maintenance costs of a building during its lifecycle far outweigh the cost of the initial investment. Even though the economic benefits over the lifecycle of a facility are evident, BIM adoption in FM is still in its infancy compared to its uptake in the architectural, engineering, and construction (AEC) phases.

Depending on the stage of implementation (Edirisinghe et al, 2017), many obstacles to making full use of BIM in FM exist, including process, technology (Eastman et al., 2011), and organisational barriers (Shen et al, 2016). BIM for FM is still relatively new, and thus market readiness and finding the right project for the organisation (Eastman et al., 2011) matters. It was recently argued that the decision to adopt BIM is related to organisational priority settings (Edirisinghe et al., 2016) during the technology initiation stage (Rogers, 1995). Challenges were particularly reported in setting organisational priorities for BIM, especially when the core business of the organisation is not asset management (Shen et al., 2016; Edirisinghe et al, 2016). Regardless, challenges exist in justifying the investment due to the benefits being largely intangible, and to the long payback period (Shen et al., 2016). FM personnel, as the final stakeholder group of the building lifecycle, are least involved in early decision making. A lack of technology readiness in organizations (Shen et al, 2016), high training costs and lengthy learning curves (Eastman et al., 2011; Kassem et al. 2015) are also significant. Technological barriers, such as unresolved interoperability between BIM and various FM technologies (Yalcinkaya and Singh, 2015; Kassem et al., 2015), availability of technology, and economic factors, are also challenges.

1.2 Organisational Dynamics

Strategic deployment of BIM is critical to realising the full potential use of the technology in a building's lifecycle while demonstrating its business value. The four core value concepts of FM (Jensen et al., 2013) were mapped to organisational value parameters as (Terreno et al, 2016) : (i) People: culture, satisfaction, and image; (ii) process: productivity, innovation, flexibility, reliability, adaptability, support, quality improvement, collaboration; (iii) economy: cost decrease, risk control, asset value, marketing improvement, financing potential; and (iv) surroundings: sustainability; economic, social, spatial.

Rogers (1995) argues that individual leader (decision makers and top management) characteristics reflect the level of support for innovation. These characteristics include the leaders' attitude to change. 'Actor-centred institutionalism' Scharpf (1997) posits the importance of the analysis of individual "actors" within the wider context of institutional influence. Thus, they combine the theories of rational choice institutionalism and structuralist perspectives (van Lieshout, 2008): "social phenomena are to be explained as the outcome of interactions among intentional actors… these interactions are structured, and the outcomes shaped, by the characteristics of the institutional settings within which they occur".

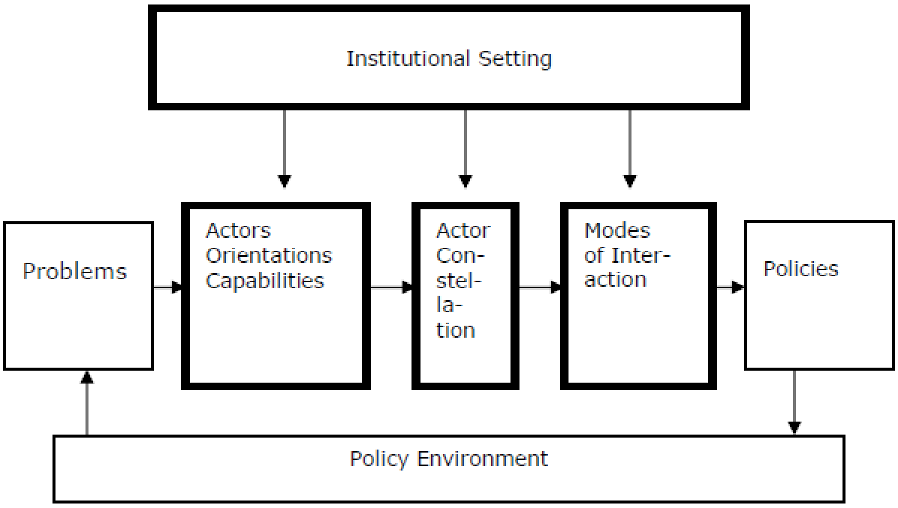


Figure 1: the domain of interaction-oriented policy research (Source: Scharpf (1997)

Through primary analysis of three case studies, Terreno et al (2016) explored how BIM can add value to FM in large owner-operator organisations – with a focus on tertiary institutions. The study postulated that the success of the implementation of BIM in FM depends on the managerial strategy, organisational culture, process and existing technological structure. Figure 1 (Scharpf, 1997) illustrates this further, showing how the policy environment introduces constraints on actors, and how the structure and influence of their institutional environment can either enable them to achieve their goals, or add further constraints.

1.3 Demonstrable real-world case studies

The absence of real-world case studies (Kassem et al. 2015; Edirisinghe et al, 2017) is another challenge while Kassem et al. (2015) also highlight the need for users to accept the technology in order for it to become more widespread. BIM-enabled facility management implementation process (Edirisinghe et al, 2017) grounded by innovation diffusion theory (Rogers, 1995) identified the knowledge gaps in BIM implementation in FM. Two technology adoption stages (Rogers, 1995) were considered in the gap analysis: (i) initiation stage - shared exemplars of early adopters' decision-making process; and (ii) implementation stage - shared knowledge base of case studies and real projects covering innovation maturity cycle (Rogers, 1995). Edirisinghe et al. (2017) highlighted the need for demonstrating real life examples of both stages to encourage wider-spread adoption.

Collaboration with "shared service peers" is important for future FM practice (CBRE&IFMA 2014). Literature also suggests that peers' effect is a motivator for BIM adoption (Edirisinghe et al, (2016). Particularly, during the initiation stage, Edirisinghe et al, (2017) argue that the leadership and knowledge management is a critical factor. It is vital to demonstrate real life examples of early adopters about successful leadership strategies and knowledge management techniques as exemplars for wider spread of BIM adoption in FM. In this research vacuum, this paper reports a case study that illustrates the journey of a higher education institution which is an early adopter of BIM.

2. CASE STUDY

2.1 Institutional Background

The organization studied is the facilities department of a large tertiary institution, whose main campus alone comprises 956 buildings, with over 1,500 Full Time Employees (FTE). The organisation is semi-autonomous within the institutional structure, receiving partial funding from the state and capital funding from the institution, and also independent as an auxiliary business enterprise. The organization's design and construction department performs most of its minor renovation projects in-house, outsourcing most new build projects, with those costing $5m and above designated as BIM projects. Most external contracts are Design-Build, Construction Manager (CM) at Risk projects, allowing for the selection of CMs who are experienced with BIM, and thus greater collaboration with the external Architects who oversee BIM projects. Asset management is also performed internally by the organization's work control unit. Following their first BIM project in 2010, the institution was one of the first in the United States to develop a set of BIM Project Planning and Execution documentation comprising a guide, template and contract language. This has defined them as pacesetters in the construction industry in relation to BIM project implementation. The study analyses how their strategic focus can aid or constrain the actions of individuals, and its influence on the strategy of the department.

2.2 Methodology

The study focused on a tertiary institution because of the large asset holdings that these organizations typically have, in addition to being owner-operators of facilities. This organization was selected from within the small sample set of institutions implementing BIM because it was one of the first adopters and due to its rapid rise to leadership within the industry. The information sought within the study was collated from documentation provided by the institution, and those publicly available online. The key players in the initial move for BIM adoption were interviewed in order to establish the initial motivation and strategies put in place to move the initiative forward.

The document reviews provided insight on the background of projects, and information on procurement and the BIM planning process. The BIM suite of documents, including project databases, published papers and presentations, and other documents were studied to extract details relating to the study and BIM efforts.

The interviews highlighted the motivation of individuals and strategies that were included as the projects progressed. Seven participants who were part of the initial effort to implement BIM in project delivery were interviewed. They are spread between strategic and tactical levels of the facilities organization, and include the academic contributors to the effort:

- Upper Management: 3 respondents
- Middle Management: 2 respondents
- Academia: 3 respondents

The data was analysed by examining the history and progression of projects against the procurement, technical and relational strategies attached to each stage of learning. The personal motivational factors of each respondent were analysed, which resulted in 10 general categories of motivating factors. The range of interests were further grouped based on specialization /managerial level for further analysis. Strategies employed were broad and varied, with the most impactful selected for discussion. In studying the benefits and challenges, the responses were grouped based on the four categories of Management, People, Process and Technology for increased clarity and comparison to other related studies.

2.3 Summary of Responses

Background

Five of the respondents indicated that the initial seed for implementation came from academia, which had long been in discussions with a member of the organisation. Their partnership led to the sponsorship of three interns to form a group which would focus on the process of BIM execution in design and construction. One respondent saw an opportunity to reverse the equation whence BIM standards were being defined by vendors and service providers; and to take a lead in the industry. The organisation's strategy was to "begin with the end in mind", thus working backwards from the requirements for operations to include these within project execution. Following widespread interviews within the FM organization, the asset management unit was the low-hanging fruit. They responded positively based on their need for efficient organization and integration of information. The design services unit registered the greatest resistance, being comfortable with their use of CAD and the smaller sizes of their projects. A detailed list of asset submittal and information exchange requirements was developed and incorporated into the new BIM Execution Planning Guide for the institution.

Table 1: Progression of BIM use in projects

			Projects		
	1	2	3	4	5
Type	Educational	Educational	Educational & Research	Medical	Athletic
Complexity	Low	High	High	High	High
Modelers	Interns	Interns & Contractors	Project Team	Project Team	Project Team
Collaboration	None	CM & Contractors	Project Team	Project Team	Project Team & FM
Contractual Requirements	None	Contractors	Project Team	Project Team	Project Team
FM data requirements	None	None	Yes	Yes	Yes

A learning process followed the implementation of the first few projects. Table 1 details this gradual progression. The opportunities were taken as the projects presented themselves. They were all large, technologically complex buildings. Modelling and coordination of the structures initially began with the Academic Interns who had the skill, but by project 2, the contractors worked together with this group and developed their own modelling capabilities. By project 3, the selected team had enough skill that the academic interns were not involved. The list of participants and collaborators of design reviews has steadily expanded to include, in the latter phases, FM personnel; with project 5 involving maintenance technicians and supervisors in the virtual reality design review. Their involvement yielded a lot of constructive feedback from the maintenance standpoint, allowing for a lot of front-end savings ahead of building occupation. The team also learnt on the job, the importance of pushing the contractual (including data) requirements to much earlier in the process for more effective project delivery.

Motivation

Table 2 below summarizes the motivational factors as described by the interviewees. Most of the respondents alluded to a commitment to the academic cause, improved project delivery and derivation of value; and more efficient FM operations. Three of the respondents (spread across the 3 organizational categories) reported being inspired by a leader; further illustrating the effectiveness of the top-down approach. One participant highlighted the flexibility afforded him which equipped him with all the opportunities he needed to take the BIM vision to the next level. Interestingly, the participant to whom the initial seed is credited had a singular focus – the delivery of value to the projects through reduction of cost and improvement of quality

Table 2: personal motivational factors of respondents

		Industry Leadership	Organizational Culture	Academic Cause	Project Delivery Process	Project Value	Efficient Data Handoff	Waste Reduction	Efficient FM Operations	Visualization	Facilitator
Upper Management	Respondent 1	✓	✓	✓	✓	✓			✓		
	Respondent 2			✓	✓				✓		✓
	Respondent 3			✓	✓	✓	✓	✓	✓	✓	✓
Middle Management	Respondent 4		✓	✓			✓	✓	✓		✓
	Respondent 5								✓	✓	
Academia	Respondent 6					✓					
	Respondent 7			✓	✓			✓	✓		✓
	Respondent 8				✓	✓				✓	

Strategies

The BIM team realized they did not have the luxury of time, and so delved into BIM implementation headfirst – knowing that there would be mistakes and adjustments along the way. Some notable strategies are listed below:

- Partnering with academia and engaging skilled interns
- Incremental change beginning with observation of the results of 3D modelling and coordination on the first project, followed by systematic additions to capital project requirements over the years (Fig. 1).
- Structuring and communicating the desired project process, including backing it up with related contract language within the BIM document suite. The requirements are standard, yet customizable by project.
- Interviewing staff to uncover the low-hanging fruit of FM asset information requirements; included in the BIM Execution Planning Template.
- An internal benchmark for success is the focus on saving 45 minutes per day in operations – it is still being pursued following the fallout of vendor-coordinated discussions, which was yet another strategy for BIM/FM integration.
- The flexibility of the BIM Group as a fee-for-service entity provided the needed flexibility that enabled their leader to pursue the vision
- "Holding the hands" of contractors, designers and project managers by providing guidance and assurance to lead them step by step towards the eventual goal. A lot of negotiation, support and encouragement went into "sneaking the change by them". One participant observed: "we realized that we needed to find a win for somebody in order for them to play... define it and make it easy for them to get there".
- Developing a progressive workforce and culture that encourages innovation. A respondent observed how the change initiative came from bottom up and noted his own role as a "mere facilitator".

Benefits & Challenges

Most of the participants celebrated the buy-in from management and FM personnel; including the obvious motivation of contractors on the project teams (Table 3). In the early stages the contractors demonstrated a readiness to take on more risk, and to step in to fill in any gaps. By the third project, they reduced their bids in anticipation of increased collaboration and 3D coordination processes. The value of visualization and better integrated information both during project execution and submittals was noted. The organisation's clients were also better engaged during model reviews, as use of navigable 3D models brought the projects to life for them, thus eliciting more interactive conversation and useful suggestions. The modelling skills of the BIM Team was a positive addition to the new projects, as many participants noted; which helped in moving the BIM initiative forward. One main long-term benefit was having a member of the BIM team now embedded within the FM department. This was viewed as a unique and advantageous move. The interviewees noted the increased efficiency in project delivery, and the increased level of collaboration during project planning and execution. One of the participants mentioned the ease of extracting operations data directly from the model as advantageous, finding most of what was needed in one place.

Table 3: Summary of the benefits and challenges of BIM implementation

	Benefits	**Challenges**
Management	Connection to Industry; Academia	Strategy
	Clear Contract Requirements	Value Proposition
	Flexibility of Operations	Funding
	External Image	Communication
People	Skilled BIM Personnel	Organizational Culture
	Buy-In from FM; Management	BIM Staff Turnover
	Motivated BIM Teams	Modelling Skills
	BIM Staff embedded in FM	Project Team Resistance
		PM BIM Skills
Process	Value: information; visualization	Handover Coordination
	Efficiency: project delivery; FM	Model Use in FM
	Effectiveness: Engagement	Scope Definition
	Effectiveness: Requirements	Knowledge Capture
	Collaboration: Teams; FM	Schedule Delays
Technology	Accessibility of Information	Interoperability
	Team Modelling Skills	
	External Influence on Industry	

Table 3 also illustrates the main challenges to BIM implementation as observed by the study participants. Interoperability of technologies was a major concern, especially in the handoff to operations. The organisation's Computerized Maintenance Management System (CMMS), Maximo, is not integrated with Revit. Therefore, in order to import the operations data into Maximo, it would need to be exported out of Revit and converted to a compatible format. This involves several options such as the manual method of Extract, Transform & Load -ETL (Ibrahim et al., 2016), data hyperlinking (Parsanezhad & Dimyadi, 2013) or use of Application Program Interface (API) coupling or such as EcoDomus, FM: Interact, Data Warehouses etc. or proprietary middleware. The Construction Operations Building Information Exchange (COBie) standard faces similar issues in data exchange, itself needing many workarounds in order to exchange data customized to an organisation's standard (Terreno et al. 2019). The problems of interoperability in the industry are further discussed by Terreno et al. (2019), where they noted that the transition of BIM data from the construction phase into operations is not as automated as generally perceived, coining this phase "BIM in Transition". Six of the participants discussed the institution's early efforts to Maximo – which is an IBM product, with Autodesk's Revit – the 3D modelling software used by project teams. Discussions had been initiated with the two vendors, bringing them together to develop a plan for data integration and seamless information transfer. These talks failed, leaving a huge problem of interoperability. The organisation's management could do nothing about the situation, as the institution has used Maximo widely across many of its campuses, these involving thousands of buildings and millions of recorded and actively managed assets. Thus, the consensus amongst management was to continue with the manual workarounds, involving thousands of man-hours per project. The coordination of the handover of information from the closeout of projects still remains a huge challenge; yet the greatest challenge observed was the unwillingness to embrace change within the greater part of the organization.

One of the main problems talked about was the issue of staff turnover. At the time of the interviews, there was no longer a BIM Group in existence. All members had left the organization / department. There was no one left to lead the project coordination efforts; nor steer the organization towards achieving the latter goal of smooth operations and maintenance within FM. This was lamented by all the upper management participants and had been unexpected - thus there was no succession plan in place.

3. Discussion

The BIM journey began with an academic push. The partnership between the organisation and academia; including the organisation's flexible business capabilities served to provide the necessary funding and skills needed to move the vision forward. Many observed that this is a unique relationship which peers admired. The wider institutional culture of fostering academic partnership, and its supporting strategy of supporting organisational innovation have contributed to this initiative. The theory of rational choice played out, as the three main actors maximized these institutional benefits by using them to achieve the envisioned goals. The external policy constraints placed by the state requiring increased efficiencies aided the strategic initiative further by providing a business case for BIM. The absence of regulatory constraints or stipulations was seen as an opportunity by one respondent to define the "BIM environment" through legacy building and institutional leadership. Within the department however, resistance by many units to change stemmed from the opposing internal culture of 'social institutionalism' as described by Scott (2005) – "the way we do these things".

Two efforts stemmed from the BIM initiative – one outward for project delivery, and one internally for automation and integration in operations and maintenance. Though two successful guides (including a project execution template, contract addendum and asset list) were produced, only one initiative registered clear success. The project delivery documentation and implementation process earned accolades for the institution, firmly placing them as leaders in the implementation of BIM in FM. However, the second initiative – though admittedly long-term – is still in the process of achieving success. The institution still struggles with efficient handoff of submittals and asset data, though the requirements have been defined and complete; and the vision of having integrated information, visualization in operations and automated data transfer from project execution is still at bay. This is attributable to the failure of the collaboration between vendors, in spite of the commitment of top management and individual actors within the organisation. The resulting situation shows that where the theory of rational choice worked for the first initiative, it failed within the second based on the failure in the collaboration with the external players crucial to the interoperability of technologies (Yalcinkaya and Singh, 2015; Kassem et al., 2015). External policies requiring some level of collaboration would have aided this cause.

However progressive, the organizational culture has proven averse to major change; similar to the observations by Shen et al. (2016). Only one unit was open to the prospect of BIM implementation – more so due to their information management challenges. The values of majority of the personnel thus fall far from the institutional direction of innovation and change. Additional top-down strategies to cultivate these value parameters are needed to further demonstrate the value of BIM to the personnel, from whom (BIM) value will eventually be required. The difficulty of finding and keeping skilled BIM staff, and lack of a system for knowledge capture further put the organization into a rut following the departure and relocation of the whole BIM group. However, the move by one of the members to operations is viewed as advantageous and is anticipated as a potentially successful strategy.)

4. Conclusions

The exploration of the story of BIM adoption in a tertiary institution yielded a broad narrative of experiences derived from interviews with the personnel involved in the first initiative. Though the initial seed came from academia, and the push within the organization was essentially bottom-up, it was found that the top-down influence of senior management greatly motivated the personnel, with the funding and trust given provided the necessary enabling environment for the development of the BIM initiative. The resulting top-down strategies put in place by upper and middle management served to move the implementation forward. External policies are also important in fostering change and innovation, as the presence of these aided the first initiative; whilst their absence may have contributed to the failure of the second. The incremental advancement of change – evidenced in interactions with the project team, systematic formal requirements and the back-end strategy of beginning with the end in mind within the organization has registered positive results. More could have been done to improve mentoring and communication; including incentives to keep skilled BIM staff. Knowledge capture and succession planning are two elements to keep in mind to enable long-term continuity of the BIM initiative. The attention or inattention to these by management can greatly influence the sustainability and downstream success of BIM implementation. Beginning with the end in mind has proven to be a successful strategy, and the leveraging of a broader set of options to achieve interoperability, or at least laying the groundwork of intellectual property early on can give the FM initiative another opportunity. The study's limitations include the fact that the case study method was selected, which is not usually sufficient in representing the current state of the industry. However, this was necessary because the organization is an early adopter, and it was considered necessary to study their efforts to glean lessons learned. These can be studied and prove significant for other organisations considering the adoption of BIM in their facilities departments. The study serves as a baseline of documentation for other research efforts to build on. Future work will focus on the documentation of experiences of other early adopters of BIM to uncover patterns, trends and lessons following comparison, to yield a richer set of information.

References

Becerik-Gerber, B., & Kensek, K. (2010). Building information modeling in architecture, engineering, and construction: emerging research directions and trends. Journal of professional issues in engineering education and practice, 136(3), 139-147.

BIM Task Group. The Government Soft Landings Policy (2012), (available online http://www.bimtaskgroup.org/wp-content/uploads/2013/02/The-Government-Soft-Landings-Policy-18022013.pdf [accessed December 2015])

CBRE & IFMA (2014). "2014 CBRE Facility Management Trend Report: Emerging Opportunities for Industry Leaders". http://www.cbre.us/services/ FMlink. (2004). "Facilities industry trends-survey results."

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors: John Wiley & Sons.

Edirisinghe, R., London, K. A., Kalutara, P., & Aranda-Mena, G. (2017). Building information modelling for facility management: are we there yet? *Engineering, Construction and Architectural Management, 24*(6), 1119-1154.

Edirisinghe R., London K. & Kalutara, P. (2016) An Investigation of BIM Adoption of Owners and Facility Managers in Australia: Institutional Case study, In the RICS annual construction and building research conference (COBRA 2015) Toronto, Canada, Sep 19-22.

Jensen, P. A., Sarasoja, A. L., Van der Voordt, D. J. M., & Coenen, C. (2013, May). How Can Facilities Management Add Value To Organisations As Well As To Society? In Proceedings of the 19th CIB World Building Congress 2013" Construction and Society", Brisbane, Australia, May 2013.

Kassem, M., Kelly, G., Dawood, N., Serginson, M., & Lockley, S. (2015). BIM in facilities management applications: a case study of a large university complex. Built Environment Project and Asset Management, 5(3), 261-277.

K. F. Ibrahim, F. H. Abanda, C. Vidalakis and G. Woods, "BIM for FM: Input versus Output Data," in Proc. of the 33rd CIB W78 Conference 2016, Oct. 31st – Nov. 2nd 2016, Brisbane, Australia, 2016. Rogers, E.M. (1995). Diffusion of innovations. Fourth edition. New York. Free Press.

Lee, S. K., An, H. K., & Yu, J. H. (2012). An Extension of the Technology Acceptance Model for BIM-based FM. In proceedings of the Construction Research Congress 2012@Construction Challenges in a Flat World (pp. 602-611). ASCE.

Liu, R., and R. R. A. Issa. "Issues in BIM for Facility Management from Industry Practitioners' Perspectives." *Computing in Civil Engineering* (2013). 2013. 411-418.

P. Parsanezhad and J. Dimyadi, "Effective facility management and operations via a BIM-based integrated information system," in CIB Facilities Management (CFM) 2014, Copenhagen, Denmark, 2013.

Scott, W. R. (2005). Institutional theory: Contributing to a theoretical research program. *Great minds in management: The process of theory development,* 37(2005), 460-484.

Shen, L., Edirisinghe, R., Yang, M. G. (2016) An Investigation of BIM Readiness of Owners and Facility Managers in Singapore: Institutional Case study, In Proceedings of CIB World Building Congress 2016, Tampere, Finland, May 30 - June 3

Teicholz, E. (2004). Bridging the AEC/FM technology gap. *Journal of Facilities Management*, 2.

Teicholz, P. (Ed.). (2013). BIM for facility managers. John Wiley & Sons.

Terreno, S., Anumba, C. J., & Dubler, C. (2016) BIM-Based Management of Building Operations. In Construction Research Congress (pp. 1855-1865).

Terreno, S., Asadi, S., & Anumba, C. (2019). An Exploration of Synergies between Lean Concepts and BIM in FM: A Review and Directions for Future Research. *Buildings, 9*(6), 147.

Van Lieshout, Harm (2008). "An actor-centered institutionalist approach to flexicurity: the example of vocational education and training."

Yalcinkaya, M., & Singh, V. (2015). Building Information Modeling (BIM) for Facilities Management–Literature Review and Future Needs Product Lifecycle Management for a Global Market (pp. 1-10): Springer Berlin Heidelberg

Construction Progress Monitoring Using BIM and QR Code

Sachin P. R.[1, *], Benny Raphael[2], Kalyan Vaidyanathan[3],
[1] M.Tech, Department of Civil Engineering, IIT Madras, Chennai, India
[2] Professor, Department of Civil Engineering, IIT Madras, Chennai, India
[3] CEO, Nadhi Information Technologies, Chennai, India
* email: sachinsriganga@gmail.com

Abstract

BIM is widely used in the design and the planning phase of projects, but it is not effectively utilised during the execution phase (Davies, *et al.* 2013). This study examines the possibility of integrating BIM into a project management framework to monitor construction progress and thus, improving the current method of progress monitoring on site. A workflow involving collection of as-built data is implemented in a live construction project and this data is stored on a BIM-based platform. The project progress is monitored with the help of a project management application which utilises sensing technology (QR code) for data collection. The technology is kept economically viable and easy to use by using equipment like wireless QR code printers and smartphone sensors (camera). The project status is updated in a cloud-based database, which can also be retrieved by scanning the QR codes printed on-site. The QR code is utilised as a simple data storage method which can hold data like location, element IDs, task IDs, status etc., which can bring in a context-aware sense to the devices like a smartphone. This data is represented using a BIM-based platform. Complex data can be easily visualised at any instant, by using this method. This enables the various stakeholders to be at the same level of understanding about the project status.

Keywords: Progress monitoring, BIM, sensing technology, QR code, visualisation

1. Introduction

Construction Progress Monitoring is a highly complex task. It involves measuring, recording and analysing the construction works most of which are done manually (Zhang, et al. 2009). It is essential for the companies to keep track of the immense amount of data generated in this process in order to ensure that the required quality of work is attained. Unrealistic planning is one of the common reason for delays. Even for a well planned construction project delays can happen and are likely to impact the project costs and schedule. These delays can be accounted for unforeseen events (Rebolj, et al. 2008). Timely action must be taken to minimise the impact of these events. A proper construction progress monitoring system must bring the information from the site to the decision makers at the right time.

Recently, Building Information Modelling (BIM) has become popular among architects and design engineers. BIM is a framework for storing several layers of information about the building that can be shared and used throughout its life cycle i.e. design, scheduling, construction, operations and demolition (Pishdad-Bozorgi, et al. 2018). It is an information centric framework where all the different stake holders can view or update the data. Although, BIM is widely used in the design and the planning phase of the project, it is not completely utilised during the execution phase of the project. In particular, the methodology to incorporate site data into a BIM model is not well developed (Davies, et al. 2013).

Automated or semi-automated data acquisition is a solution for obtaining data with good accuracy and available in a timely manner. Many scanning based techniques can be utilised to collect actual data from the construction site (Mayer, et al. 2018). Technology such as barcodes and RFID have been available in an economic way in the market. The increasing amount of data in construction sites require streamlined and automated information flow. QR codes and RFID can deliver this in an efficient manner without the loss of quality (T. Omar, et al. 2016). A similar tracking system involves April tags, which are a type of fiducial marker which are placed at fixed locations in the building, whose locations are marked as per the 3D model previously generated (Nahangi, et al. 2018). In a study conducted using RFID as a technology to improve management efficiency, it was used to collect data which was later interpreted statistically. A web based facilities management system in Taiwan was studied in this work and the application of RFID was validated. It was found that RFID helped improve the efficiency (Ko, 2017). The RFID tags having GPS capabilities to easily identify the location of the tags are also available but tend to be costly due to the added benefits of better range, no line of sight required and durability (Akinci, et al.2006).. For a general user of a smart phone the easiest method to update data by phone is by scanning QR codes (Pan, et al. 2017). The collected data can be regulated within an IT framework and used for decision making (El-Omari, et al. 2011).

Photogrammetry, Laser scanning and computer vision technology have been utilized to make quality as-built models. These techniques integrated with BIM have been proven to be very useful (H. Omar, et al. 2018). In another study conducted, improving the construction management capacity using a three phase approach was done. It includes three systems each for identification of location, monitoring the work progress and visualization & statistical analysis. Bluetooth Low Energy beacon is utilized for collecting the location information from each worker. The BLE is an IoT technology which can be used for collecting location data even in complex environments like a construction site. This data is used to create heat maps and is compared with the construction progress data for analysis and decision making (Han, et al. 2017). Several studies for monitoring construction projects using image recognition based activity tracking system are being conducted (Senthilvel, et al. 2017). In a study conducted, the author presents the system as a solution to ensure flow of information. The data is collected on site and is converted to information on-time which has helped improve project performance. The image based system tries to compare the as built and planned models of the project. by extracting 3D geometry using photographs from multiple cameras. The images help in representing one-to-one, one-to-many, many-to-one, as well as many-to-many relations with the BIM and different stages of the activity as per the schedule (Rebolj, et al.2008). In a similar study a new automated approach for collecting data using unordered photos and BIM is used (Golparvar-Fard, et al. 2011). The author brings to the point that the current method of data collection brings in significant amount of data but are inefficiently presented, which results in poor decision making. The author suggests that monitoring must be effective, of low or no cost, automated and be represented in a feasible format which can be read and understood by all personnel involved (Golparvar-Fard, et al. 2015). Project management applications are being used extensively in construction projects where smartphones and PDA are utilised for progress monitoring (Kimoto, et al.2005). A construction site where the as-built data is collected using a project management application is selected for the study. Although the data was centralised and accessible for the stakeholders, the cloud based application could not provide location awareness to the users. The sensing technology is utilised for providing this accessibility and thereby improving communication.

This paper examines the possibility of integrating BIM with a data collection framework to enable timely communication and visualisation. A new workflow has been developed in which the progress monitoring data is collected using QR code scanning and is represented in a BIM based platform. The workflow is tested out in a live construction site to improve the existing progress monitoring process using QR codes to collect construction progress data.

- Testing the feasibility of a BIM and QR code integrated workflow on-site.
- Identification of issues and challenges faced in the implementation.

1.1 Current Practice

The current practice as observed at the selected construction site (hereon referred to as construction site), is depicted in Figure 1.

1. A site engineer from the contactors side looks after the activities at the worker level.

2. When an activity is completed, the site engineer applies for a Request for Inspection (RFI) through the project management application.
3. Once the RFI is posted the quality engineer from the client side gets a notification in the application.
4. He has to then go inspect the corresponding request and approve or reject it using his mobile application.

In large projects, the inspection task will be tedious as identification of the corresponding element is really hard.

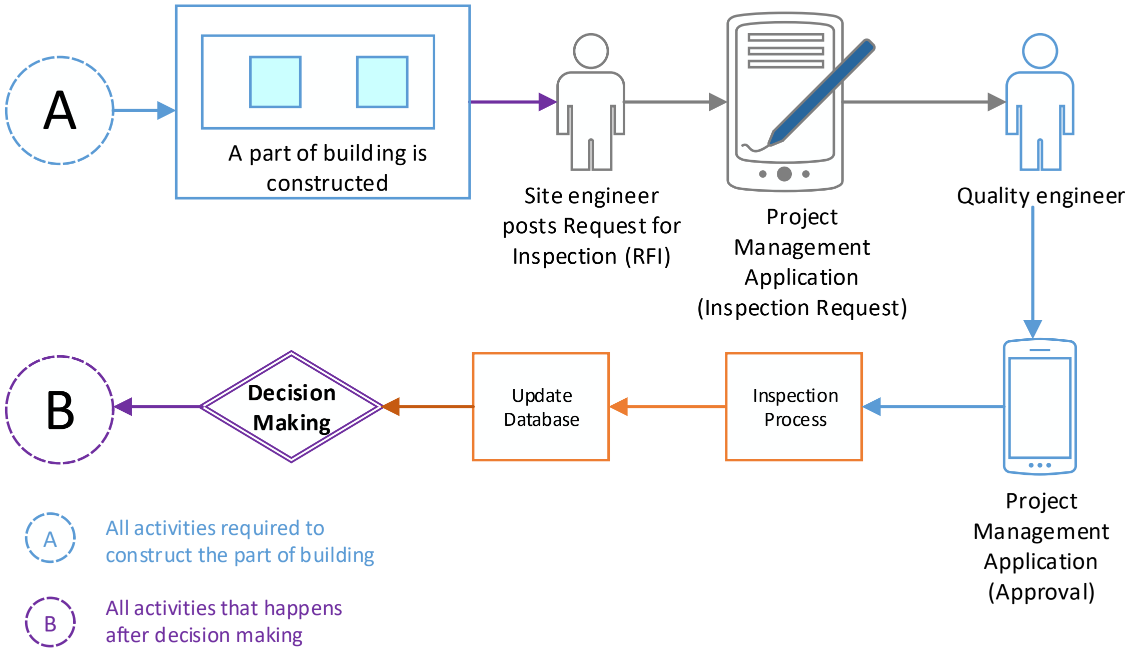


Figure 1: Current workflow practiced on-site

The following are observed at the selected construction site.

- An IT infrastructure for monitoring the project is implemented at the construction site.
- BIM is provided by the architect but it is used only for generating construction drawings for the contractor.
- BIM is not utilised for scheduling, progress monitoring or visualising the information.
- The information exchange can be made effective by integrating BIM in the above activities i.e. scheduling, progress monitoring and visualisation. This can be achieved by:
    - Mapping BIM and current schedule
    - Using this mapped data for progress monitoring using the application
    - Visualising the collected data from site on BIM based platform

1.2 Implementing the new workflow

A new workflow has been developed for improving the monitoring of the construction process. The schedule mapped to the BIM model is utilised as an input for the new workflow. This data is updated in real-time using the project management application ***nPulse*** **(**http://nadhi.in/**)**.

Different tasks involved in the modified workflow are summarised in

Table 1. Key personnel involved in monitoring are listed in Table 2. Software modules used for creating the support framework for project monitoring is given in

Table .

Table 1: Framework for project monitoring

Sl. No.	Type	Tasks
1	Pre monitoring tasks	• Prepare BIM • Prepare schedule • Mapping of BIM element ID to tasks in schedule • Upload the mapping to nPulse database
2	Tasks during monitoring	• Construction activity completion • Posting of RFI and printing QR code • Approval / Rejection of activity • Update database
3	Tasks after monitoring	• 3D model based on BIM • Get data from updated database in real-time • Visual feedback of data in database • Decision making

Table 2: Personnel involved in the Progress Monitoring

Sl. No.	Role	Description
1	**Site Engineer**	• Contractor's engineer • Overlooks the construction task as per the drawings, specifications and schedule • Responsible for posting RFI and printing QR code on completion of the task using the nPulse site engineer module
2	**Quality Engineer**	• Owner's engineer • Responsible for the quality inspections • Overlooks the dimensional stability, material used, reports on strength tests • On approval using the nPulse Quality engineer module the accounts section approves the funds to the contractor

Table 3: Software required for collecting data from site

Sl. No.	Name	Description
	Postgre SQL	Database Management tool. Enable the developer to query data from the schedule stored in the database
	Apache Tomcat	Create local server to enable communication between the

		mobile device and the database
3	Nadhi nPulse desktop	It enables the users to access the project information. The GUI enables the users to add, edit, analyse and visualise the data
4	Nadhi nPulse mobile application	The project management mobile application that has the QR code scanner. It communicates through the server to access the database whenever required

The equipment needed for implementing the workflow include the following:

1. A wireless pocket printer that can be connected to smartphone using Bluetooth technology for QR code printing. It is lightweight and can be carried to construction sites with ease.
2. A smart phone that can run nPulse project management application. The application provides the interface for scanning QR code using the phone camera.

A portable wireless printer is used for printing QR code. A sticker type of paper is used for printing. The QR code printed will be stuck on to the respective element corresponding to the task in hand. On scanning the QR code all the necessary details about the corresponding task can be seen by the engineer. Once the task details are approved by the engineer the as built BIM model will be updated.

Procedure:

1. Each task on a building element is completed by a group of workers under the site engineer.
2. The site engineer completes initial inspection and posts the RFI using the nPulse application. He prints the QR code and attaches it to the corresponding element.
3. This appears as a notification on the quality engineer’s module. He then updates the inspection time and other instructions through the application.
4. The quality engineer comes to the site and scans the QR code. All the related documents of the corresponding element appear on the application, and he can begin the inspection.
5. On approval of the task, the schedule is updated and also the accounts department will be notified for initiating fund transfer to the contractor.
6. The site engineers and other authorised personnel could scan the QR code to find the current status of the element, the documents attached to it. If the task is not approved the list of rejected checklists can be viewed

The workflow is shown in Figure .

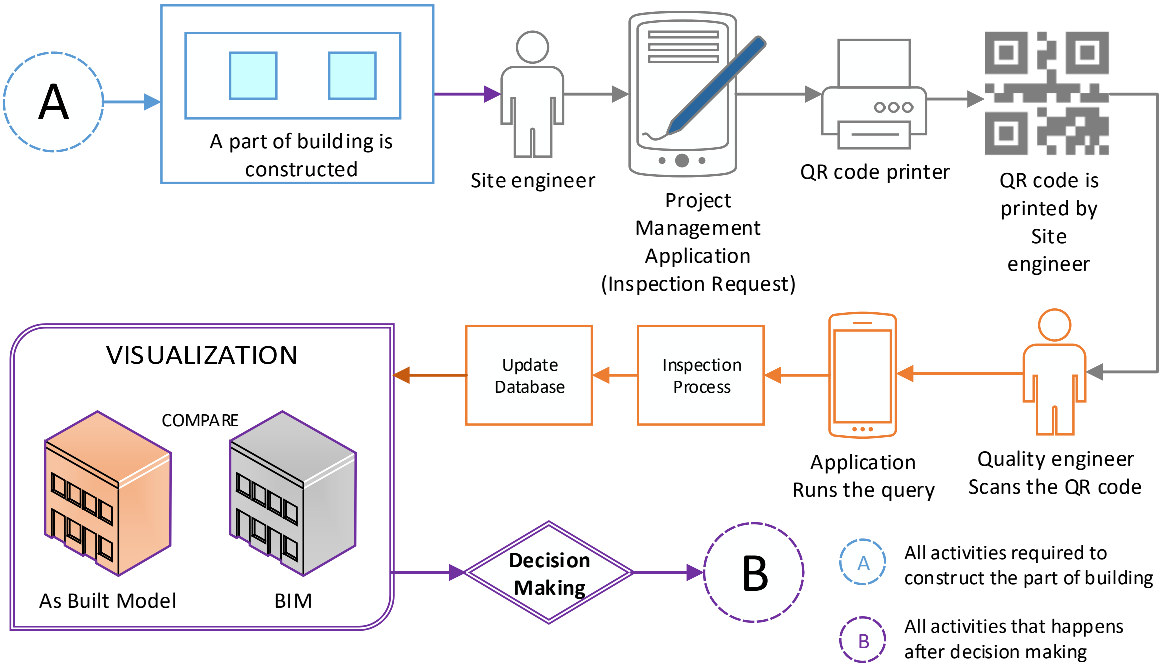


Figure 2: Workflow using QR code technology

2. Evaluation

The framework was evaluated on an actual construction site. The selected project is a commercial building situated at Porur in Chennai, India. The building is being developed by ***Company A*** (client and quality engineer) with the help of ***Company B*** (architect), ***Company C*** (contractor) and ***Company D*** (project manager). ***Company B*** provides the design details and BIM. ***Company C*** is bound by a design and build contract to ***Company A***. ***Company D*** provides the project management support and the IT infrastructure for progress monitoring and communication among the stakeholders.

Company B and ***Company D*** operates remotely whereas ***Company A*** and ***Company C*** have setup fully fledged site offices to carry out the construction and monitoring activities.

The client insisted on a thorough monitoring system for the purpose of creating a good accounting database. The transfer of funds for a particular activity only happens when the quality engineer approves of the construction activity in the project monitoring device. This updated information is instantaneously visible for the client's accounting team and fund transfer will be initiated.

2.1 Progress monitoring at selected construction site

The workflow for the Project Monitoring was designed after collecting observations and recommendations from users for 10 days. The new workflow was implemented and was tested for two weeks. The parameters listed in Table were collected in order to evaluate the performance of the monitoring system.

Table 4: Table showing the distribution of points for various parameters

Parameters	**4**	**3**	**2**	**1**	**0**
	very good	**good**	**Ok**	**bad**	**no result**
Functionality	worked in first try	worked 2-4 tries	worked after few tries	worked after many tries	did not work

Scanning distance	> 2.0	1.0 - 2.0m	0.5 - 1.0m	< 0.5	nil
Environment	sunny day	cloudy	Rainfall	heavy rainfall	NA
Durability	> 24 hours	24 hours	8 hours	1 hours	can’t be used
Lighting	> 200 lux	200-101 lux	100-51 lux	50-11 lux	< 10 lux
Network	very good	good	Ok	bad	no network
UX	very good	good	Ok	bad	did not work

All the readings were taken for the foundation level activities and therefore the QR codes were exposed to the exterior environmental forces. This led to readings showing low durability, when compared to readings taken in an indoor condition. Similarly, the lighting parameters have low values and are subject to large variations, as all the elements selected are exposed to the outdoor conditions. There was no fluctuation in the network during the period of the experiment.

The functionality aspect will be high or low depending on the errors in the application, hardware or network. The users in the selected construction site are already familiar with the nPulse application. The quality engineers were asked to carry the QR code wireless printer in order to print it. The user experience was collected at the end of the experiment as per the Table 5.

Table 5: Points distribution for the different readings taken from the construction site

Sl No.	Element	Task	Unique BIM_ID	User	Functionality	Scanning distance	Environment	Durability	Lighting	Network	UX
					Points (0-4)	*meters*	*Points (0-4)*	*Points (0-4)*	*Points (0-4)*	*Points (0-4)*	*Points (0-4)*
1	Column	Concreting	1610340	self	4	0.5	4	4	1	4	NA
2	Column	Concreting	1610323	self	4	0.5	4	4	1	4	NA
3	Raft	Concreting	1216823	self	3	0.5	1	2	4	4	NA
4	Raft	Concreting	1216823	self	0	NA	4	4	4	4	NA
5	Pile Cap	Reinforcement	2579828	self	4	0.5	4	4	4	4	NA
6	Pile Cap	Reinforcement	2580645	self	4	0.5	4	4	4	4	NA
7	Slab	Formwork	887860	self	4	0.5	4	4	4	4	NA
8	Pile Cap	Reinforcement	2593830	self	4	0.5	4	4	4	4	NA
9	Pile Cap	Formwork	2669725	self	4	0.5	4	4	4	4	NA
10	Pile Cap	Reinforcement	2594911	self	4	0.5	4	4	4	4	NA
11	Pile Cap	Formwork	2593937	self	4	0.5	4	4	4	4	NA
12	Column	Concreting	1604237	self	4	0.5	1	0	1	4	NA
13	Column	Concreting	1610601	self	4	0.5	1	0	1	4	NA
14	Column	Reinforcement	2577186	self	0	NA	1	0	4	4	NA
15	Column	Formwork	1608553	self	0	NA	1	0	4	4	NA
16	Column	Reinforcement	1608320	engineers	4	0.5	4	4	4	4	3
17	Column	Reinforcement	2573145	engineers	4	0.5	4	4	4	4	3
18	Pile Cap	Formwork	2592167	engineers	4	0.5	4	4	4	4	4
19	Pile Cap	Formwork	2592124	engineers	4	0.5	4	4	4	4	4
20	D-wall	Reinforcement	2052871	engineers	4	0.5	4	4	4	4	3

The summary of readings taken for the various activities are given as the following.

Functionality: The functionality parameter showed the highest working condition for most of the readings. It can be seen that three of the readings shows that the workflow did not work at all. This was primarily due to the bugs in the application. The testing also served as a method to find bugs in the nPulse application.

Scanning Distance: The scanning distance is 0.5 m for all the readings taken. Each of the readings taken are at closely accessible locations. It was tested and found that the camera was unable to scan the QR code beyond 0.5 m.

Environment: This parameter refers to the environmental condition. It is relevant to the experiment as the current on-going activities are all exposed to the external weather conditions. The observation table shows that the weather conditions were either sunny or rainy.

Durability: Durability was tested using custom modified QR code samples. The QR code was covered in a thin transparent plastic film to protect from rain and dust. It was observed that the paper stayed intact by using this method. But, the QR code became unreadable in 48 hours due to an induced chemical reaction between the printed ink and the glue used to stick the plastic film. Use of costlier, better quality paper could further improve the durability of QR code.

Lighting: The lighting aspect was tested using the light-sensor in the smartphone. It was seen that for the readings taken open to sky the lux values were high and was easily scanned by the smartphone camera. When the QR codes were under the shade the readings were below 50 lux. This problem can be easily tackled for smartphone cameras with built-in flash.

Network: There were no obstructions as the construction activities are still happening at the foundation level. However, network issues are expected to be a problem as soon as the superstructure begins to envelope the construction activities.

UX: The user experience was collected from the site personnel involved in the data collection.

2.2 On-site observations

Some images of using QR codes on site are shown in Figure 3. Several challenges that need to be overcome for successfully implementing project monitoring using QR code in a construction site were identified, including the following:

- Weather condition is a critical factor for durability.
- Low lighting condition did not affect scanning since built-in flash lights in the smart phones could be used, but locating the QR code was difficult.
- Several tasks and activities like concreting and reinforcement cannot be monitored, also activities involving inaccessible areas like overhead slab formworks.

a. QR codes fixed on the rebars   b. QR code placed near a newly cast concrete slab

Figure 3: QR codes on-site

2.3 User Interface for visualisation

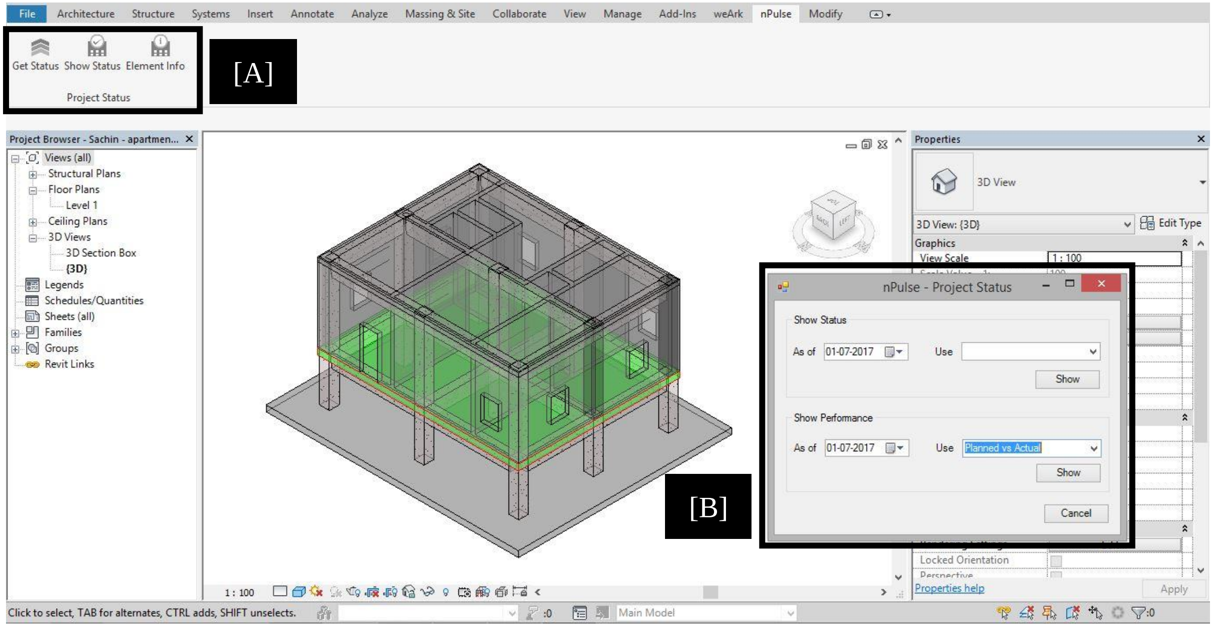


Figure 4: Graphical User Interface- developed as an addin for Autodesk Revit

The Graphical User Interface (GUI) implemented is shown as per the Figure 4. The plugin is developed using the Autodesk Revit API. The plugin links the online database with the BIM model. The graphical parameters are modified using the plugin to achieve the required results. The GUI has buttons to obtain user inputs, perform database queries and update 3D model.

For illustration, the visualization of project status is shown in Figure 5. The user can query any date within the project timeline and request to highlight the elements that have any task attached to it in any of the planned, actual or estimated dates. This functionality allows the user to visually understand the different activities that will happen at the construction site on a particular day.

The query with planned dates can be viewed throughout the project timeline. It is the baseline schedule that is prepared by the planning engineers. The actual dates will be able to show the construction works that was actually done for the selected day. This is a very relevant viewport for the different stakeholders, as this can show the real-time activities that have happened in the construction site.

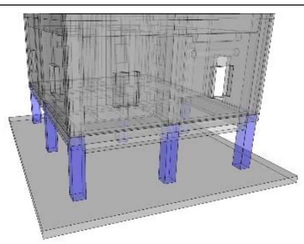
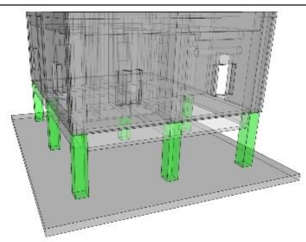
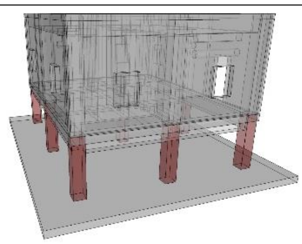
Planned	**Actual**	**Projected**
		
Planned work for the selected date is highlighted as blue	Actual work for the selected date is highlighted as green	Projected work for the selected date is highlighted as brown

Figure 5: Visualising project status

3. Concluding remarks

This study tried to resolve few construction site challenges in a practical manner. In this research, a new framework for construction progress monitoring using existing technology like QR code and BIM has been developed and tested. The new workflow implementation has improved the efficiency at the construction site by making information easily accessible due to the location aware query feature.

Visualisation of data is given utmost importance in this study. The database is updated in real-time during the inspection process by scanning QR codes using the application. The project manager is able to obtain up to date information about the status of the project through the user interface. Clarity in communication leads to better project management.

The implementation on an actual construction site demonstrated the feasibility of applying the framework to complex construction projects. The study also brought out the limitations of the QR code technology.

Acknowledgements

The authors would like to acknowledge RMZ group for providing the construction site and data for the pilot-testing. We thank the L&W group for the support from their site engineers. We also thank team Nadhi Information Technologies for their valuable technical support.

References

Akinci, B., Kiziltas, S., Ergen, E., Karaesmen, I. Z., & Keceli, F. (2006). Modeling and Analyzing the Impact of Technology on Data Capture and Transfer Processes at Construction Sites: A Case Study. *Journal of Construction Engineering and Management*, *132*(11), 1148–1157. https://doi.org/10.1061/(asce)0733-9364(2006)132:11(1148)

Davies, R., & Harty, C. (2013). Implementing “site BIM”: A case study of ICT innovation on a large hospital project. *Automation in Construction*, *30*, 15–24. https://doi.org/10.1016/j.autcon.2012.11.024

El-Omari, S., & Moselhi, O. (2011). Integrating automated data acquisition technologies for progress reporting of construction projects. *Automation in Construction*, *20*(6), 699–705. https://doi.org/10.1016/j.autcon.2010.12.001

Golparvar-Fard, M., Bohn, J., Teizer, J., Savarese, S., & Peña-Mora, F. (2011). Evaluation of image-based modeling and laser scanning accuracy for emerging automated performance monitoring techniques. *Automation in Construction*, *20*(8), 1143–1155. https://doi.org/10.1016/j.autcon.2011.04.016

Golparvar-Fard, M., Peña-Mora, F., & Savarese, S. (2015). Automated Progress Monitoring Using Unordered Daily Construction Photographs and IFC-Based Building Information Models. *Journal of Computing in Civil Engineering*, *29*(1), 04014025. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000205

Han, Y., Yashiro, Y., & Hatori, F. (2017). A Visualization System for Improving Managerial Capacity of Construction Site, (Isarc), 3–10.

Kimoto, K., Endo, K., Iwashita, S., & Fujiwara, M. (2005). The application of PDA as mobile computing system on construction management. *Automation in Construction*, *14*(4), 500–511. https://doi.org/10.1016/j.autcon.2004.09.003

Ko, C.-H. (2017). RFID, web-based, and artificial intelligence integration in facilities management. *ISARC 2017 - Proceedings of the 34th International Symposium on Automation and Robotics in*

Construction, (Isarc), 333–338. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85032356295&partnerID=40&md5=d58fb7a22a3f2017e52fc56e52b22afe

Mayer, P., & Modelling, B. I. (2018). The automation of the process of updating the curing time activity in 4D schedule, (Isarc).

Nahangi, M., Heins, A., Mccabe, B., & Schoellig, A. (2018). Automated Localization of UAVs in GPS-Denied Indoor Construction Environments Using Fiducial Markers, (Isarc).

Omar, H., Mahdjoubi, L., & Kheder, G. (2018). Towards an automated photogrammetry-based approach for monitoring and controlling construction site activities. *Computers in Industry*, *98*, 172–182. https://doi.org/10.1016/j.compind.2018.03.012

Omar, T., & Nehdi, M. L. (2016). Data acquisition technologies for construction progress tracking. *Automation in Construction*, *70*, 143–155. https://doi.org/10.1016/j.autcon.2016.06.016

Pan, N. H., & Chen, K. Y. (2017). A study of BIM based building facilities online repair system. *34th International Symposium on Automation and Robotics in Construction, ISARC 2017*, (Isarc), 352–357. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85032381669&partnerID=40&md5=75bd1e86ccea6912706b4a7f082e11d0

Pishdad-Bozorgi, P., Gao, X., Eastman, C., & Self, A. P. (2018). Planning and developing facility management-enabled building information model (FM-enabled BIM). *Automation in Construction*, *87*(February 2017), 22–38. https://doi.org/10.1016/j.autcon.2017.12.004

Rebolj, D., Babič, N. Č., Magdič, A., Podbreznik, P., & Pšunder, M. (2008). Automated construction activity monitoring system. *Advanced Engineering Informatics*, *22*(4), 493–503. https://doi.org/10.1016/j.aei.2008.06.002

Senthilvel, M., Soman, R. K., & Varghese, K. (2017). Comparison of Handheld devices for 3D Reconstruction in Construction. *Proceedings of the 34th Int. Symp. Autom. Robot. Constr.*, (Isarc), 698–705. Retrieved from http://www.iaarc.org/publications/fulltext/ISARC2017-Paper097.pdf

Zhang, X., Bakis, N., Lukins, T. C., Ibrahim, Y. M., Wu, S., Kagioglou, M., … Trucco, E. (2009). Automating progress measurement of construction projects. *Automation in Construction*, *18*(3), 294–301. https://doi.org/10.1016/j.autcon.2008.09.004

Towards an automatic approach to generating BIM models from digitized plans

Omar Doukari[1,*] and David Greenwood[2]
[1]CESI Centre de Paris Nanterre
[2]Northumbria University
[*] email: odoukari@cesi.fr

Abstract

This paper proposes a new approach to creating BIM models of existing buildings from digitized images. This automatic approach is based on three main steps. The first involves extracting the useful information automatically from the digitized plans (in .TIF, .JPG or .PNG image formats) by using image processing techniques (including segmentation, filtering, dilation, erosion, contour detection). This information will feed the knowledge base of an expert BIM model generation system. Secondly, using the knowledge base of the expert system, the information that will inform the BIM model can be deduced. Finally, an Industry Foundation Classes (IFC) model can be automatically generated with all the desired geometric, physical and technical information.

Keywords: Automation, Digitized Plans, Knowledge, Expert System, Artificial Intelligence

1. Introduction

A Building Information Model (BIM) is a database containing information relating to a built asset. It can represent not just the geometry of the building and its contents, but all its physical and technical characteristics (Aram *et al.*, 2013; Doukari *et al.*, 2017). Over the last ten years, BIM has become, according to Celnik *et al.* (2014), the most discussed and utilised new technological tool in the field of construction. However, though its usefulness and benefits have been demonstrated in several fields of application (e.g. Ji *et al.*, 2013; Lee *et al.*, 2011; Kim *et al.*,2013; Kim *et al.*,2016) creating a BIM model can be a laborious task that requires the collaboration of several modeling teams over time. This is the case with a new asset: when it comes to modeling an existing asset (for example, retro-modelling an existing building to take advantage of a digital model for maintenance purposes) this can quickly become particularly expensive. First, there is the use of expensive technology, such as laser scanning equipment, post-processing and BIM modeling software. Then, expert intervention is required to identify certain information and characteristics of the various components such as types of materials (Zeibak-Shini *et al.*, 2016). On the other hand, the cognitive processes of the human expert might be reproduced automatically using artificial intelligence, using tools such as neural networks, expert systems, and genetic algorithms. The first step would be to represent human expertise in a machine-readable format, then to define reasoning operators that can, based on certain information, draw relevant conclusions (Gevarter, 1984). In this paper, we propose a new approach to creating BIM models of existing buildings from digitized images. This automatic approach is based on three main steps. The first involves extracting the useful information automatically from the digitized plans (in .TIF, .JPG or .PNG image formats) by using image processing techniques (including segmentation, filtering, dilation, erosion, and contour detection). This information will feed the knowledge base of an expert BIM model generation system. Secondly, using the expert knowledge base of the expert system, the information that will inform the BIM model can be deduced. Finally, an Industry Foundation Classes (IFC) model can be automatically generated with all the desired geometric, physical and technical information. We present a proof of concept as well as the conceptual model of an expert system for automatic generation of such BIM models. An algorithm for extracting information from digitized plans, developed in Python, together with a knowledge base, represented in the form of rules of production, are also presented. The successful application of such a system would overcome the constraints of time and cost when creating a BIM model of an existing built asset.

2. Methodology

Our approach is essentially based upon the use of programming and image-manipulation tools such as: Python, OpenCV, NumPy, SciPy, Skimage (scikit-image), and Matplotlib. The approach follows the stages that are shown in Figure 1, each of which is explained in the subsequent text.

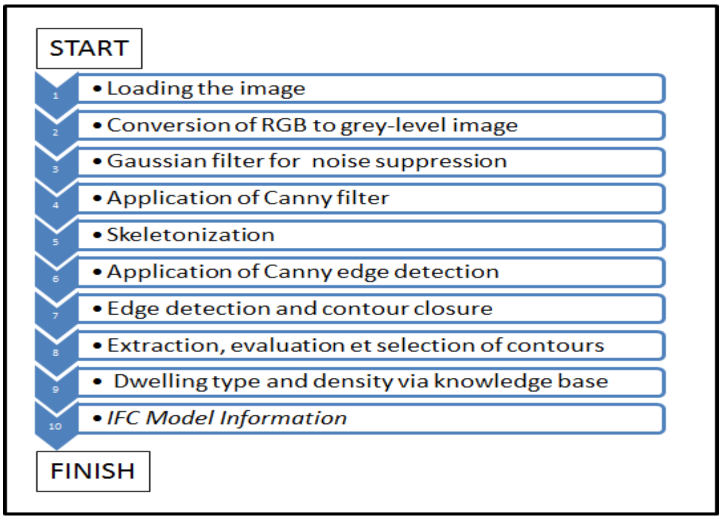


Figure 1: Stages in the algorithm for BIM model generation

2.1 Data

Two types of data were chosen, namely, cadastral sources (maps) and satellite images (see Figures 2 and 3, respectively) of a part of Nanterre, a suburb of Paris. The original format of the data is .TIFF, .JPEG or .PNG and each represents a surface area of 1 hectare.

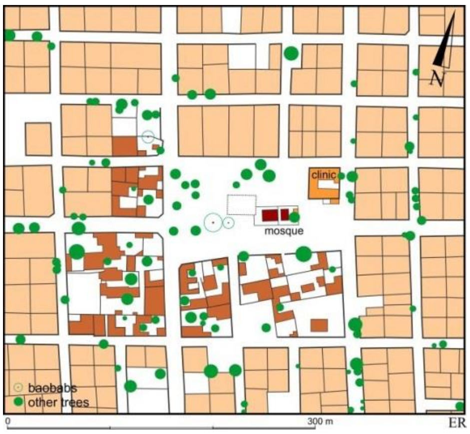


Figure 2: Section of a cadastral map

Figure 3: Satellite image (Google Earth)

2.2 Manipulation of the data

The application of the above algorithm to the cadastral map (Figure 1) produces the results shown in Figures 4 to 8, which are accompanied by a short description of the process.

Conversion of image from RGB to grey-scale: To simplify the data input we have chosen to work with monochromatic images. The RGB colour images are therefore converted to grey-level, as shown in Figure 4.

Gaussian filter: The occurrence of random noise information in the image reduces its sharpness. To reduce the noise an important step is to smooth the image using the Gaussian filter (see Figure 5).

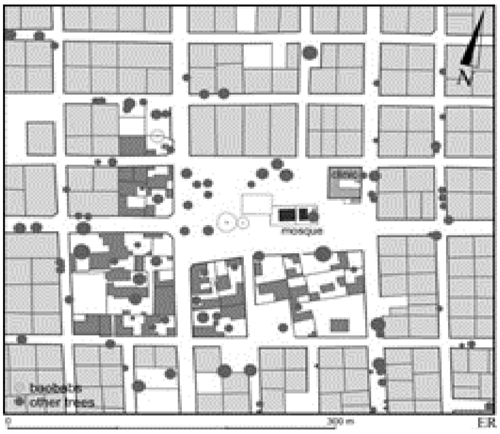


Figure 4: Source image converted to grey-level

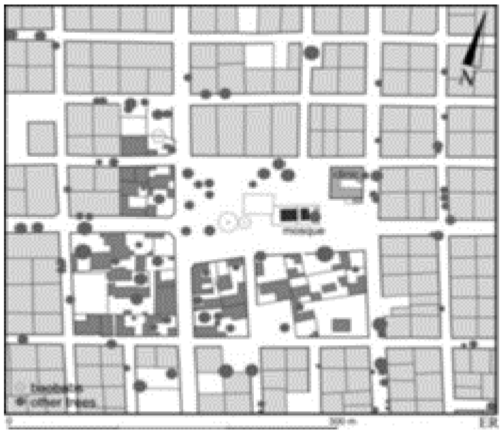


Figure 5: Image after 'smoothing' using Gaussian filter

Canny filter application: The Canny filter is then used to: (i) minimize the error rate in edge detection, (ii) minimize the distance between the detected contours and the actual contours, and (iii) return a single response by contour. To draw only the contours, it uses a calculation of the intensity gradient followed by a hysteresis thresholding of the contours in order to have a binary image; with the outlines in white and the other points in black. This one is sensitive to noise and in order to avoid an increase in localization error, it is necessary to carry out a pre-treatment to suppress this. The detected contours also depend on the value of the thresholding. This varies from one image to another. There is no value in detecting all good outlines for all images.

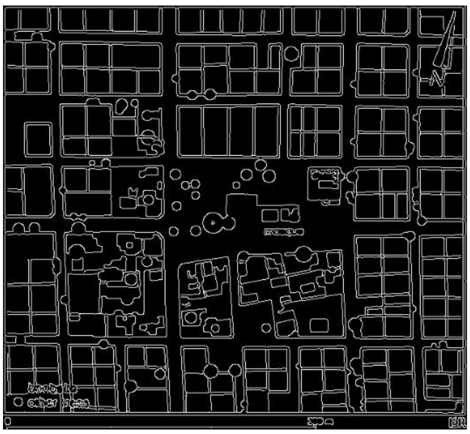


Figure 6: Image resulting from application of Canny filter

'Skeletonization': This stage may be necessary where there are shapes with irregular contours that require treatment by reducing and weakening their shapes into a curve called a skeleton. This enables an average contour to be obtained in cases where the size of the contours is not uniform. In the case shown in Figure 5, however, the process is not necessary and skeletonization had no effect.

Canny Contour Detection then detects all the contours of the previous image, in particular the coordinates of the points that make up the contours in a vector.

Extraction, evaluation and selection of contours: After closing of the contours the next step is to select those that are of interest: i.e. those that are likely to represent buildings (as opposed to vehicles, natural spaces and other images that do not represent built assets). This is done by calculating the area and perimeter of the contours before selecting and distinguishing (using colour) those that appear to be of interest.

Figure 7: Image with highlighted contours of interest (338 contours detected)

Closing contours: The problem of unclosed contours remains (Figure 8). This distorts area calculations, counting, and contour selections. These are shown in close-up (zoomed) in the following Figure 8.

Figure 8: Image close-up showing unclosed contours

In order to solve this problem, a new algorithm was developed that can detect the ends of open contours and connect them to the nearest pixels in their vicinity. Some approximations were made during the tests. In its current state, this algorithm allows at least 70% open contours to be closed. As a result, a total of 588 contours are detected (Figure 9) as opposed to the original 338 contours.

Figure 9: Image after closure of contours (588 contours detected)

In order to retain only the contours relevant to our study, i.e. contours potentially representing buildings, the results are again filtered to keep only contours whose area is between 30 m² and 1000 m². (Figure 10).

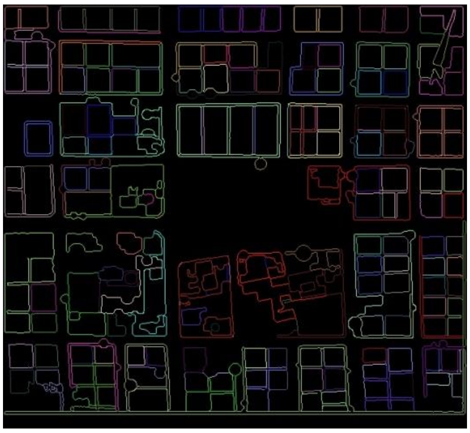


Figure 10: Image after selection of chosen contours (178 contours selected and coloured)

Following this, the results can be seen alongside the corresponding section of the original satellite image (see Figure 11, as an example).

Figure 11: Section of the treated data (4 contours alongside original image of 4 individual houses).

Once the relevant contours have been selected, the useful and usable information is extracted into an Excel file, particularly the area and perimeter of the contours. It is also possible to extract the coordinates of the approximated points of the contours, that is to say, the edge points of each segment

2.3 Knowledge Base and IFC File Generation

In the realm of Artificial Intelligence, a knowledge base is a technology used to store complex structured and unstructured information used by a computer system. The first use of the term was in relation to the expert systems that were the first knowledge-based systems; computer systems that emulate the decision-making abilities of human experts. The term "knowledge base" was adopted to distinguish itself from the widely-used “database”, as by the 1970s, most large information systems managed their data stored in hierarchical or relational databases. An expert system is principally composed of two modules: an inference engine and a knowledge base (Figure 12). The knowledge base includes a set of defined rules that serve as a reference for extracted facts. The inference engine applies the rules to known facts to infer new facts and new information. In some cases, an inference engine can also provide explanations for the results obtained.

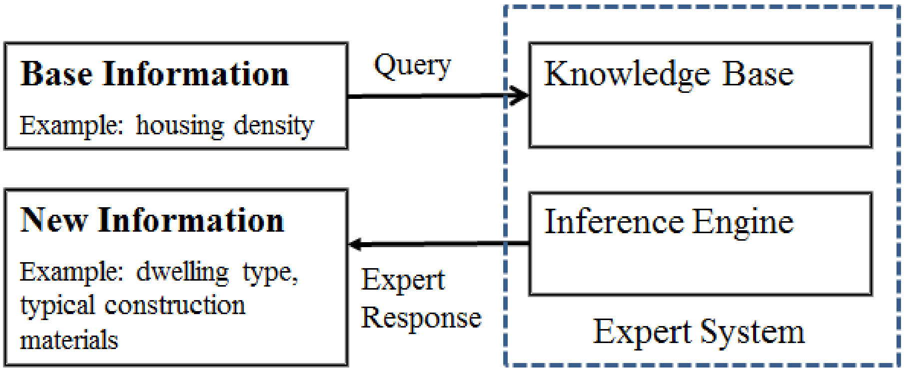


Figure 12: Conceptual view of an expert system

Expert systems are designed to solve complex problems by reasoning on knowledge, represented in a given formalism: logical, ontological, production rules, etc. The latter is the one adopted as part of this study. Since we are working on images whose area is 1 hectare then the number of buildings detected will correspond directly to the density of housing. Thus:

Housing density = Number of dwellings / Site area (Ha)

Given that we are working on images whose area is 1 hectare then the number of buildings detected will correspond directly to the density of housing. In France, buildings are classified by geographical zone (urban, suburban, rural, etc.) and according to type. In order to simplify automation, the different types of housing are also variously classified (e.g. as detached, semi-detached, terraced, dense housing complex, etc.) according to types that commonly occur throughout the regions of France.

The following table (Table 1) is a simplified version of the knowledge base as so far as it currently extends.

Table 1: Knowledge base of dwelling type, surface area and construction materials

Min. density	*Max. density*	*Dwelling type*	*Surface area (m2)*	*Materials*
1	4	Suburban villa	180	Block – Tile – Concrete - Wood
5	8	Housing estate	130	Waterproofed Insitu concrete
9	10	Individual Grouped	125	Stone – Concrete – Brick – Wood
11	15	Detached town house	116	Brick - Concrete
16	50	Single terraced	108	Brick - Concrete
51	80	Intermediate	89	Brick - Stone

81	121	‘Grand Ensemble’	78	Brick - Concrete
122	212	Multiple occupancy	69	Insitu reinforced concrete
213	343	High-Density Multi-occupancy (Centre Bourg)	45 to 90	Stone - Concrete
344	1000000	Built-up area (Hausmannian fabric)	30 to 120	Brick – Concrete - Brick

From the knowledge base created, the type of housing and the type of materials that it is typically composed of can be readily deduced. In the case of the previously discussed satellite image, the resulting inference is that the dwelling is part of a collective housing complex and the material of construction is brick and concrete (see Figure 13).

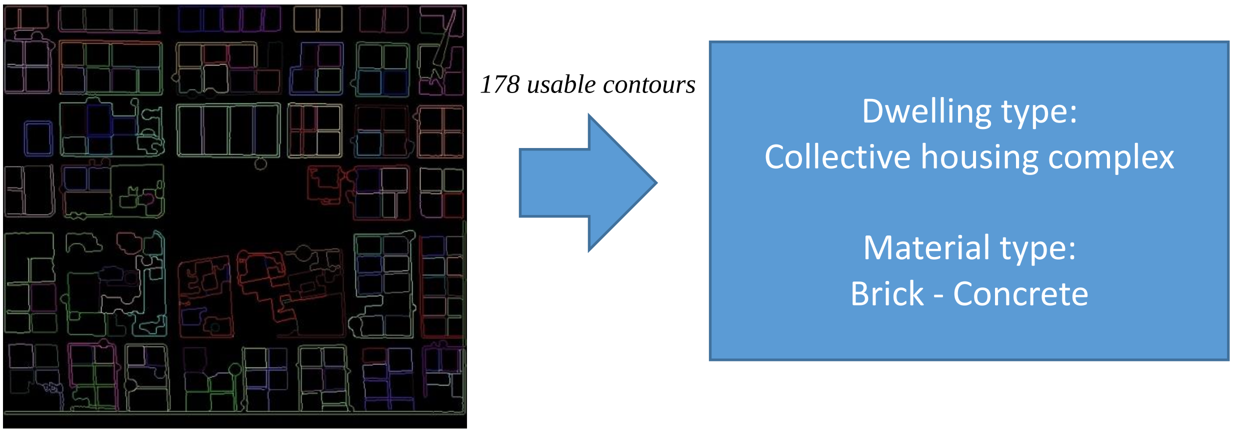


Figure 13: Results of expert system query

Generation of IFC model: This stage of the process is, as yet, in its development stage. The aim is to develop a program that allows the population of a model ("blank IFC") with all the information derived from the image processing at the urban scale, as exemplified in this article, together with the images of the facade of the building of interest, i.e. the one for which we wish to generate the BIM model. New information such as the number of levels, openings, doors, rooms, etc. could easily be derived from this second category of images and inserted into the "IFC blank" file. The APIs offered as part of the "IFC TOOLS PROJECT" project (see Doukari *et al.*, 2017 and the website http://www.ifctoolsproject.com). which include IFC object class development libraries, would be utilised for the completion of this stage.

3. Conclusion and perspectives

The use of BIM in the construction and property sectors is increasing, and as it does so, further benefits are becoming evident. However, the creation of a BIM models can be expensive and time-consuming, particularly in the case of the existing stock of built assets, where the required information (both geometric and non-geometric) needs to be retro-fitted into a model using a variety of scanning and other techniques. Thereafter human expert intervention is required to fully develop the information in the model. Here, the possibility is explored of automating the modelling process by developing artificial intelligence that replicates and replaces certain of the cognitive processes that are elements of the human expert intervention.

In this article, we have illustrated an algorithm that automatically retrieves information about the area, the perimeter of a building, and the housing density of a region (limited to 1 hectare). We have also demonstrated the creation of a knowledge base with an expert system able to deduce new information such as the type of housing or the type of materials used. The final step of generating and populating an IFC BIM model based on information already derived is currently under development.

This task will be based on the tools developed as part of the 'IFC TOOLS PROJECT' (see Doukari et al., 2017 and the website http://www.ifctoolsproject.com).

References

Aram, S., Eastman, C., & Sacks, R. (2013). Requirements for BIM platforms in the concrete reinforcement supply chain. Automation in Construction. 35 (0) (2013) 1–17.

Celnik, O., Lebègue, E., & Nagy, G. (2014). BIM et maquette numérique pour l'architecture, le bâtiment et la construction. 1ère ed. Paris: Eyrolles & CSTB.

Doukari, O., Naudet, B., & Teuilier, R. (2017). « Merging IFC-Based BIM Models: A new paradigm and co-design support tool ». International Journal of 3-D Information Modeling (IJ3DIM), 6(1).

Gevarter, B. W., (1984). Expert systems: Artificial intelligence applied. Telematics and Informatics. Volume 1, Issue 3.

Ji, Y., Borrmann, A., Beetz, J., & Obergrießer, M. (2013). Exchange of parametric bridge models using a neutral data format, J. Comput. Civ. Eng. 27 (6) (2013) 593–606.

Kim, H., Anderson, K., Lee, S., & Hildreth, J. (2013). Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology. Automation in Construction 35 (0) (2013) 285–295.

Kim, H., Shen, Z., Kim, I., Kim, K., Stumpf, A., & Yu, J. (2016). BIM IFC information mapping to building energy analysis (BEA) model with manually extended material information. Automation in Construction 68 (2016) 183–193.

Zeibak-Shini, R., Sacks, R., Ma, L., Filin, S. (2016). Towards generation of as-damaged BIM models using laser-scanning and as-built BIM: First estimate of as-damaged locations of reinforced concrete frame members in masonry infill structures. Advanced Engineering Informatics, Volume 30, Issue 3.

Professional pathways in BIM and digital construction

Kathryn Davies
Unitec Institute of Technology, Auckland, New Zealand
email: kdavies@unitec.ac.nz

Abstract

Increasing complexity in construction projects, together with widespread availability of technology applicable to many aspects of the construction industry, is driving demand for greater integration of information and communication technologies. The resulting transformations in technology and process require associated changes in professional roles and relationships in a digital context. Development of any professional role is a dynamic process, with no determined transition point when a profession can be considered to exist or not. Instead there is a cycle of development as skills, expectations, and specialisations evolve and are modified to suit the changing environment. This concept of the professional life cycle forms the framework for an exploration of changes in roles and practice in the context of digital construction. While traditional construction industry functions and responsibilities take place within well-established professional roles, a multiplicity of views has emerged regarding the status of roles which encompass digital construction. This paper uses practitioner narratives to explore aspects of technology adoption and implementation that are having an impact on the way such careers develop. Interviewees were selected who identified themselves, or were identified by their peers, as BIM specialists; many of these individuals also described involvement in broader digital construction initiatives. Taking BIM practice as a starting point, career factors identified by these practitioners are connected to a wider perspective of digital maturity in the industry, and to the concept of the professional life cycle: as digital practice continues to change and mature, the career possibilities and needs within the field also evolve. The findings show that the introduction of digital construction has progressed to a point where BIM is now common across many sectors of the AEC industry, and a range of other digital applications are becoming increasingly mainstream. This move to digital construction in many cases takes place within traditional roles that have expanded or changed to suit the changed environment. In other cases, new roles have emerged to fulfil specific needs for digital management of information, process and strategy in projects and organisations. However, even with this increasing involvement of specialist practitioners in BIM and wider industry practice, the status of digital construction with regard to professional roles is still not established. Many practitioners expressed feelings of insecurity regarding their current position, suggesting that work to provide greater clarity around career progression is necessary so that practitioners can be assured that digital skills have value and recognition.

Keywords: digital construction, professional identity, BIM roles, professionalisation,

1. Introduction

Development of professional roles is a dynamic process; there is no single moment when a profession can be considered to come into existence. Instead, there is a cycle of development, as skills, expectations, and specialisations evolve and are modified to suit the changing environment. This is evident in the multiplicity of views that has developed regarding the status of BIM as a professional role (Bosch-Sijtsema et al., 2019). As the wider context of digital construction develops, similar uncertainty exists in the status of practitioners specialising in other aspects of digital practice.

Roles in digital construction currently have little uniformity in titles or expectations. BIM is the most established element of digital construction, but the definition of industry standards and norms is still ongoing. Individualised practice from early BIM development has led to diverse descriptions of

BIM roles and associated practices, and BIM handbooks and guidelines both within national markets and internationally contain overlaps and discrepancies in how various roles are named and defined (Davies et al., 2017a). The lack of clarity regarding BIM professional roles and opportunities has been identified as a contributing factor in the shortage of skilled practitioners. Many universities are now attempting to address the skills shortage by introducing programmes to develop BIM skills in their graduates. However, education and training providers require definition of professional expectations and standards so that their offerings are suitable to meet industry needs. Practitioners currently in the industry need similar guidance enable them to upskill themselves into BIM positions. Equally, without such information, graduates and current practitioners are likely to be less interested in pursuing opportunities in BIM and digital construction as the direction and outcomes are unknown.

Nonetheless, while this may lead to misunderstandings about areas of responsibility and authority on project teams, there is still an overall consensus regarding which BIM roles are required at an organisational and project level. Currently, and for at least the near future, BIM practice necessitates the introduction of specialist practitioners, and also requires traditional practitioners to become involved in digital construction, taking them beyond their established positions. Development in other aspects of digital practice is now gaining pace in the construction industry, as BIM becomes a springboard for the adoption of other digital innovations (Rogers, 2019). Notable technologies include augmented and virtual reality, robotics, 3D printing, digital fabrication, laser scanning, photogrammetry, Internet of Things, digital twins and the many possibilities of artificial intelligence. However, despite rapid change and the proliferation of opportunity in this area, the industry appears still unable to resolve the names and types of technologies included under the "digital construction" banner, let alone the roles and practices that they entail. Thus, the routes practitioners have taken in establishing roles in BIM serve as an example of the possible evolution of other digital technologies, in terms of establishing digital construction as a professional pathway.

BIM practice is presented within a life cycle perspective that shows a continuum of development, beginning with early digital innovations, evolving through BIM adoption and connecting to other current and future digital construction technologies. BIM practitioners' views are presented regarding the development of a professional identity through BIM practice. Related issues are then presented around different ways that BIM implementation and identity interact with the decision to adopt a BIM career. The subsequent discussion considers more overarching aspects of BIM practice which may influence practitioners' decision to embrace or reject BIM as a career choice, including the potential development of roles within the professional life cycle framework.

2. Method

The following analysis is based on interviews carried out in New Zealand, Australia, The Netherlands, the United Kingdom and the United States, with 73 BIM specialists from a variety of roles, disciplines and company types. Participants either had a formal job description involving BIM (e.g., BIM manager, BIM coordinator) or were identified by their peers as the BIM champion or BIM leader in their company. Companies represented were equally diverse, and ranged from global multi-disciplinary consultancies which have been identified as world leaders for providing digital services in construction, through to small independent practices employing just a few people and finding their way into BIM adoption.

Loosely structured interviews were used to explore the impact of BIM on professional roles and relationships. This interview format provides a framework so that specific issues can be addressed, but has the flexibility to allow in-depth exploration of the interviewees' varied opinions and experiences (Alvesson, 2011). Clandinin and Connelly (2000) argue that such a narrative approach is pertinent to study experience in a professional context, since narrative is central to how practitioners reflect on experience and relate it to practice.

The interview data was collected over the period 2013-2015. Although this means that aspects of BIM practice reflected on by the participants are not necessarily still current, the focus of this paper is not on the state of BIM but on how professional identity and roles have developed for BIM practitioners. Consequently, the perspectives from an earlier stage of BIM development are appropriate for application to a discussion of emerging roles related to digital construction. Several studies of identity have previously been conducted within the construction environment. Gluch (2009) explored the identity of environmental professionals in a construction project context, and called for further research on the emergence of new professional roles in construction and their relationship with traditional roles and professional expertise. Identity of site-based construction workers has been examined from the perspective of quality (Styhre, 2012) and safety (Andersen et al., 2015), both studies concluding that practitioners' identity can be influential in shaping organisational and project outcomes in relation to practice. Other studies exploring the professional identities of project managers (Hodgson & Paton, 2016) and construction managers (Brown & Phua, 2011) also suggest that identity studies provide insights into practice, and argue the need for further research into identity work in professions in relation to the potentially conflicting demands of social, organisational and industry expectations. Based on these antecedents, the use of interview data with a focus on identity to explore the development of professional roles in digital construction is appropriate.

Thematic analysis was used as the primary approach for analysis of the interview data, using the methodology outlined by Braun and Clarke (2006). Thematic analysis involves "searching across a data set …to find repeated patterns of meaning" (Braun & Clarke, 2006; p86), and involves an inductive coding process to identify and refine themes. The preliminary activity involved transcribing and editing interview recordings, followed by structural coding, based on the research questions and interview framework, in order to assign codes to features within the data that were related to the research questions and sub-questions (Saldaña, 2013). Several iterations through the data were required to code and collate the entire data, in a process that progressively served to develop a research 'storyline' (Stuckey, 2015). Once codes had been assigned to all of the data, each category was revisited, and broader patterns of action and interaction were identified. At this stage, the themes were reviewed to ensure they were clear and distinctive, and the connection to the storyline was established. This required a further iterative process of revisiting themes and reviewing in the wider context of the full data set. Re-coding and revising data was then carried out to refine the themes. Through this process, practitioner identity was established as one of the central themes. Representative quotes from the interviews have been used to illustrate the experiences and opinions expressed by participants, in order to connect the data into a theorised storyline (Golden-Biddle & Locke 2007).

3. The professional life cycle

A professional life cycle is concerned with the changes and developments in professional roles related to an innovation, that lead to the institution of a new professional service or practice. Professional roles develop in the wider industry context beyond both individual and organisational levels, and must balance the different needs and pressures of other factors such as the requirements of project partners and clients, and competition and relationships with other practitioners. A life cycle model of a professional service was proposed by Lawrence et al. (2016), in the context of LEED consulting roles. This model has been applied here to BIM and digital construction, and the changes that are taking place within the professional community as they become an established part of the industry.

A life cycle view of professionalism views BIM maturity from the perspective of the developing professional role of the BIM practitioner. It presents a progression path that is driven by the tension between customisation and standardisation. Lawrence et al. (2016) structures the life cycle into four stages: innovation, validation, diffusion and commodification. Service delivery and expectations move through each stage as practice progresses. Figure 1 illustrates the life cycle model of the BIM and digital construction professional environment, adapted from Lawrence et al. (2016).

At the very beginning of the life cycle, innovation is driven by experimentation and unique solutions, and is dependent on individual creativity. In the BIM environment, this has produced a multiplicity of adoption and implementation approaches as individuals have become enthused about BIM's potential and have introduced it into their company's practices. These individuals have often come from technical backgrounds; consequently, much of early BIM development focused on technical and process implications of BIM (Miettinen & Paavola, 2014). More strategic views of BIM adoption tend to occur at later stages of the professional life cycle, and have broader ramifications for the associated roles and the ways in which practitioners operate in the evolving BIM environment. BIM can be used to deliver benefits without necessarily involving users in collaborative practice with other project participants (Davies et al., 2017b), but much of the advantage that can be derived from BIM

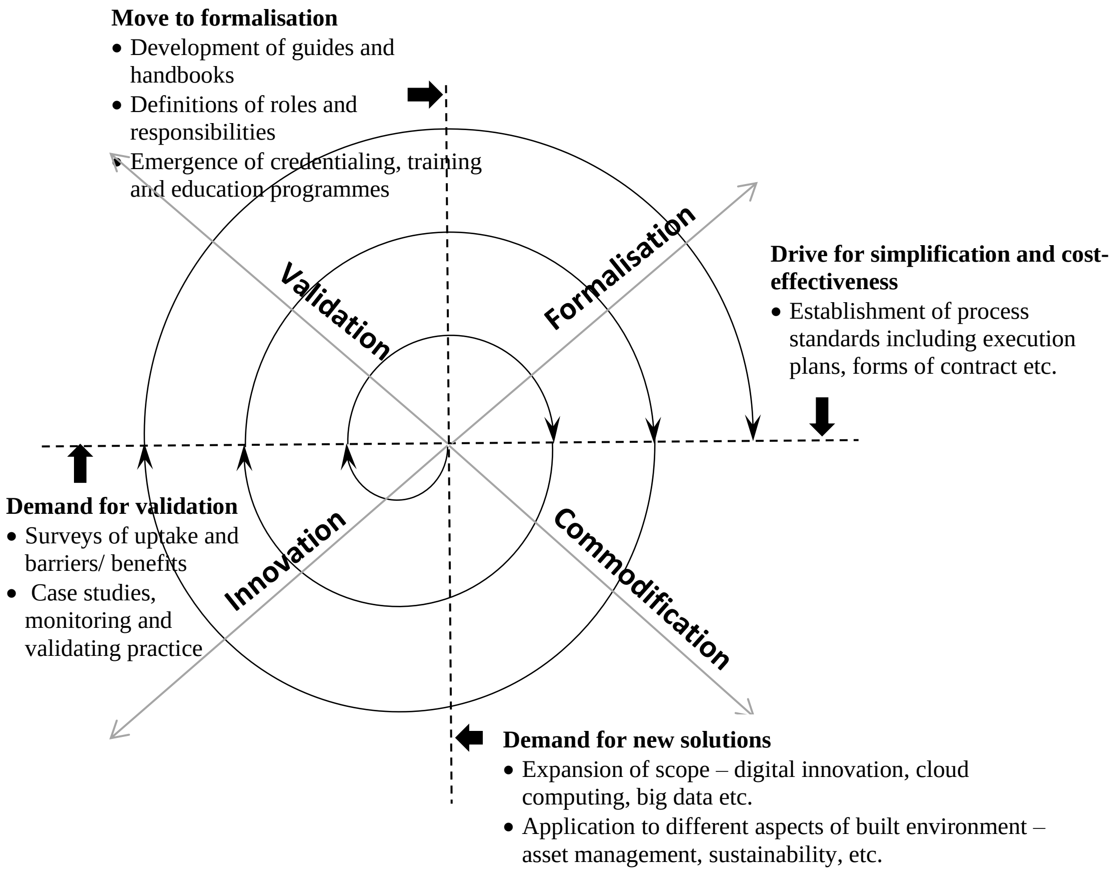


Figure 1 Life cycle model of digital construction as a professional service (after Lawrence et al., 2016)

adoption lies in the move to more collaborative project environments (Poirier et al., 2016). This transition requires further innovation by practitioners, to promote and manage the change in practice.

The second stage of the professional life cycle, validation, occurs when initial innovations draw wider attention, and more emphasis is then given to measuring and documenting outcomes, and to validating practice to ensure skills and knowledge are evaluated and monitored. Reported benefits from initial innovators in BIM increased demand across the industry, as outcomes reported for early-stage BIM development were generally highly positive. Individual companies sought to customise the successes of others for use in their own circumstances. This led to an increased drive for technical expertise, and high demand for skilled staff. Validation in the BIM context started at the relatively low level of establishing benefits and requirements of BIM, resulting in an initial validation stage based extensively on surveys and reviews of BIM uptake and benefits and barriers, and debate over roles required.

In the third stage of the life cycle, formalisation, the industry calls for formalised education and accreditation processes as the innovation takes greater hold and the practice becomes established. The many BIM guides, handbooks and other standards and specifications now available are evidence of the formalisation effort that has taken place in BIM. Much of this is to do with BIM practice rather than the professional roles involved, but the frameworks and standards also transfer into more defined requirements for skills and tasks of practitioners. Credentials for BIM practitioners have also started to emerge alongside expectations for training and education options. The advantage of this formalisation process is that practitioners have access to a foundation of support material such as case studies and standards to build their practice on. This allows them to establish baseline expectations quickly. As availability and use of these documents and the associated professional standards and credentials become more widely adopted, they feed back into validation processes at another stage of the cycle.

Once formalisation has been addressed, the final stage of the professional life cycle comes into play. Commodification leads to the basic activities involved in the profession becoming standard practice, through which they are simplified and regulated. This means that practitioners can follow practice guidelines and focus on straightforward implementation, rather than having to develop their own approaches. Those with greater knowledge are then freed up to develop innovation, for example expanding the scope of BIM to incorporate other industry innovations or interests, or moving practice into new areas of application, and thus moving the cycle through another iteration.

In this way, the professional life cycle model provides a framework for monitoring and directing progress in the development of BIM as a professional role. By using the life cycle model as an overview of the professional continuum, the interests of practitioners can be matched to appropriate roles as the stages progress. When disproportionate emphasis is placed on one stage of the cycle, as currently appears to be the case with innovation, it is difficult for the role to mature.

4. Professional identity

Identity work is an ongoing process of reflection and sensemaking that takes place at multiple levels (Lepisto et al., 2015). Expression of identity in a work environment is primarily concerned with how an individual prioritises their knowledge and skill within their work activities. Identity work in a professional context is relational, in that it commonly takes place in response to pressure and expectations of others; for example, direction from managers, examples provided by industry or professional leaders or other role-models, or defined models of behaviour established by professional memberships. Professionals must negotiate the value and importance of these various relationships with respect to the developing identity, in order to establish legitimacy in the role that they are claiming.

The BIM practitioners interviewed often had considerable latitude in determining both their own role and how they enacted BIM practice within organisations and project teams. Because they were appointed or moved into a new role within an organisation that often had little or no experience of BIM practice, they frequently had a significant influence on setting the direction of BIM practice within the organisation. Many noted that they were employed in their current role for the specific purpose of implementing BIM for their company. Even where an organisation already had a BIM framework in place, it was common for interviewees to state that they had no specific job description, and often that they did not have a formal position in the company structure or hierarchy. Individuals were in many cases responsible for determining the scope and requirements of their own position.

> My task isn't on paper what I should do, so I just make things myself. I have to make my own function, I still have to make it, my job description. I have to figure out for myself what it is.
> *Interview 43—The Netherlands, Construction company*

As a result, the professional identity of the practitioners had a significant impact both on their own roles and on how BIM and digital construction developed in their practice environment. Two identity frameworks were used to investigate different aspects of this. First, *claimed identity* looked at how practitioners positioned themselves in relation to professional practice, BIM experience and motivation, based on their statements that claimed or rejected views of their identity in relation to BIM. This is related to narratives of how practitioners performed their BIM roles, and how they saw themselves connecting from their professional level with organisational and industry level identities. Second, *performed identity* reveals the different enthusiasms that practitioners bring to their role, and approaches they take to their BIM practice. The performed identity is not simply what people do in a BIM role, but why they do it; the motivation and drivers for their BIM interest and involvement.

4.1. Claimed identity

Not all of the practitioners were comfortable in claiming a BIM practitioner identity, or accepting the ‘BIM specialist’ label that they had been given by their peers. Although they were associated with BIM, these practitioners either did not see it as part of their professional identity, or were not confident that they have the necessary skill or commitment to claim a BIM practitioner identity. The identity work for practitioners who refused the BIM identity outright commonly downplayed the BIM component and focused on their discipline role. They often identified very strongly with a traditional industry role, and saw BIM as just one of a range of tools or skills that was useful in achieving their primary goals. Respondents in this category included architects, an architectural draughtsperson, and a quantity surveyor. All agreed that BIM was a central part of how they worked, and that they were interested and engaged in using BIM as well as developing and sharing their BIM knowledge. Despite their level of involvement, however, BIM was not just incidental to their professional identity but was actively rejected in their narratives; they did not consider themselves a "BIM professional."

Tentative acceptance of the identity came from several practitioners who were interested and willing to develop a BIM identity based on their level of interest and knowledge in BIM, but with the caveat that they weren't 'really' involved in BIM. Their identity work asserted the value of BIM to them personally, but ascribed their status as a 'BIM specialist' less to their own expertise per se, and more to the slight advantage they held over the general level of ignorance in the wider industry. There was also an element of cautiousness with many practitioners in claiming solo or hybrid BIM use as 'real BIM'. The low level of BIM knowledge in the industry was both blamed for restricting the use of BIM, and credited for elevating the interviewees, with what they considered their incomplete or insufficient BIM skills, to the status of BIM specialists. Another source of hesitation in claiming BIM identity lay in the lack of definition of BIM roles. Practitioners in many cases observed that their status within their organisation and project teams was unclear, to others and even to themselves.

> The roles are not defined very well. It's a very unusual kind of way of working, and it's what you make it as well. You get people screaming at you from some perspectives, and other perspectives are like 'I don't know what you do, I don't even know why you work here, I don't know what your role is.' It's probably something that I think sometimes too!
>
> *Interview 14—Australia, Multi-disciplinary design practice*

Because of this lack of clarity regarding their role, practitioners felt they were open to challenge from colleagues, and unsure of their authority or ability to act. While they may have been willing to accept a professional BIM identity based on their own knowledge and skill, the absence of identity in relation to the organisation and wider industry left them in a tentative position.

More widespread were the practitioners who claimed BIM as part of their professional identity, but who emphasised that it was just one aspect of their role. Peer recognition of a BIM practitioner role was one of the challenges for a number of the participants, who considered that their contribution was often considered secondary, suggesting that "there is sometimes that tendency [to see you as] just the technician" (*Interview 2—NZ, Multi-disciplinary consultancy*), even when their qualifications and experience were equal to those of their peers. Many practitioners in architectural practices were often at pains to make clear that their identity did not lie solely in being a BIM practitioner, but that they had design skills and involvement as well. Similarly, in construction companies, practitioners often emphasised their breadth of experience, to illustrate that they were not 'just' BIM practitioners.

> I've done lots of engineering stuff, I'm very technical-minded. One of the criticisms of most people in BIM is that they're not, there's not much commercial focus there.
>
> *Interview 57—UK, Construction company*

A sense of risk was expressed in the narratives of a number of interviewees who balanced BIM identity alongside another professional alignment; a concern that BIM may become a dead-end path rather than offering the prospect of a new career direction. One interviewee described the BIM direction as people having "deviated away from their careers" (*Interview 46—UK, Multi-disciplinary consultancy),* and indicated that in future he could switch back to his previous design-focused role. In this case, despite his successful career and rapid promotion to a senior BIM role, such a comment indicates that 'BIM practitioner' is not a core part of his professional identity.

For others, however, the evolving role was not seen as a conflict, but as an opportunity to develop additional skills and add or extend parts of their role that they enjoyed. Being identified as a BIM practitioner, in this mindset, was an opportunity to test out a new professional identity, without having to commit fully to one or the other.

> They call me a BIM specialist. It's a big word! Three years ago, the manager asked me to come and work here because they wanted to do BIM. He didn't know what BIM was, but he heard BIM is hot so we had to do BIM. I had a little experience in introducing BIM in an organisation. He asked me, will you do the same here. I'm still a cost engineer. I come from within the projects and I like estimating the cost, just digging deep in the project. But I also like to talk with people, let them know what they're doing right and what they can do better. So I'm also the BIM manager at some projects. *Interview 44—The Netherlands, Cost consultancy*

Expressions used to describe this diversification from an intended career path included "another string to my bow" and having "different hats if I want them". Other interviewees saw it the other way around, and identified that having an architecture or construction background could be 'a safety net' to revert back to if their current role turned out to be unnecessary beyond a transitional stage of BIM adoption.

A minority of participants fully accepted a BIM identity, and did not qualify their BIM identity with 'but', 'and' or 'almost'. To these individuals, all of their experience and the range of tasks and activities they were involved with did not detract or sit alongside their BIM identity, but contributed to the characteristics of the role they had constructed. In this case, the identity work asserts the practitioners' holistic professional identity, claiming all the varied aspects of their job as part of the BIM role.

4.2. Performed identity

Narratives in which participants described their expectations, motivations and ambitions in relation to their roles were examined to identify how practitioners articulate their professional identity in relation to performance. Five core types were identified that reveal the different enthusiasms that practitioners bring to their role, and approaches they take to their BIM practice. These types are not fixed or exclusive, and some practitioners described adapting their persona to deliver the outcomes they see as necessary at a particular time. This sense of balancing identity across multiple roles corresponds with the debate from industry over whether BIM generalists are more valuable, given the range of work that BIM practitioners might be expected to carry out, or whether the depth of knowledge required to effectively deliver BIM within a particular discipline means that specialists are necessary (Wu and Issa, 2013). Participants described their roles in terms that include elements of most, if not all, of these identities, but tended to emphasise or express a particular identity type that they feel most closely represents themselves—their personality, aptitude, performance, and preferred ways of working. The identity types are not simply *what* people do in a BIM role, but *why* they do it; the motivation and drivers for their BIM interest and involvement.

The following five types of BIM performance identity were identified from the narratives (with representative quotes in italics):

1. <u>Implementer</u> – "*I'm the kind of person who will work it out, and make it work*"; pragmatic, task focused, using BIM to provide value.
2. <u>Interpreter</u> – "*I can find out things that are better for another person than he could decide or find out by himself*"; interface between people and technology, translating technology into industry context.
3. <u>Instructor</u> – "*There would always be myself falling into a training role to teach them how to do things*"; supporting others in skills development, teaching people how to make better use of BIM.
4. <u>Inquirer</u> – "*I'm always looking into why. It's a very important question in my life.*"; not satisfied with following a process, has a need to know all of the angles.
5. <u>Innovator</u> – "*A kind of person… that needs to be a couple of steps ahead*"; sees BIM as a stage in an improvement process, more drawn to advancing the industry than to BIM specifically.

Most of the BIM practitioners interviewed came into BIM via a technical orientation, which aligns with the *Implementer* identity. An interest or aptitude for CAD or BIM tools, or for IT and computing more broadly, led to their identification as a technical leader within their company, which often then became a BIM champion role because they knew more about the software and technology process than anyone else. Although this may have led to the technical aspect of their work being overtaken by other elements of the BIM role, the practical implementation aspect, generally focused around technology, has remained a core element of practice for many, and 'making things work' was a central part of their identity narrative. Several practitioners in the implementer type identified that their motivation does not come from using BIM as a tool or technology, but is based more on the appreciation that BIM enables them to contribute in a meaningful way to the final product, i.e., the built environment that results from their efforts. In this sense the implementer role may also have a creative impetus that contributes to the motivation of the practitioners.

> It's one of the things that drives me, that satisfaction of achieving a building, you hear that from a lot of people who have been in the construction industry for a long time, they love driving by a building and saying, 'I worked on that.' *Interview 70—US, Construction company*

For some practitioners, the desire to make things work was not so much about doing it themselves but in enabling others to work more effectively. Practitioners whose BIM identity was more other-centred than self-centred have been labelled *Interpreter*. In an interpreter role, the practitioner sees themselves as a bridge between BIM and those using it. This identity is based on understanding the different and potentially conflicting needs of different project partners or industry parties, and being able to act as a broker to enable BIM adoption and implementation. Practitioners with an interpreter identity often expressed a need for variety and challenge in their role. For these individuals, this came not just from making things work, as for the implementer identity, but from coming up with new approaches or processes that address specific problems that other practitioners may be facing. The work to interpret or interface between users and the necessary technology and processes was commonly underpinned by a desire for improvement, enhancement or simplification of existing practices. Interpreter tends to be a process-focused role, but also contains a strong element of working to develop and upskill other practitioners.

> One thing I've always had is three or four people, up to 12 people, that I work with, share the basic skills and coach people through things. I'm better at that than independent work... If there's a problem that needs to be solved, I can solve the problem, say 'this is how you solve it', but not necessarily doing the leg work, turning the handle after that… Hence why working with a team works for me because I know where my weaknesses are, so I know the people I need to target to help fill that gap. *Interview 57—UK, Construction company*

Where this aspect of sharing skills and knowledge dominated over the problem-solving aspect, the professional identity has been labelled the *Instructor*. The need for BIM practitioners to take a leading role in educating other members of their organisation and supply chain has been identified in the literature (Succar et al., 2013) and is evident in job advertisements for BIM roles (Uhm et al., 2017). Thus it was not unexpected that peer-to-peer teaching, organisational training, and industry coaching and education was noted by almost all participants as a significant component of their role. For some interviewees, however, the instructor role was their motivating purpose as a central element of their BIM practitioner identity. Several noted that they had fallen into informal teaching roles during their studies or in previous positions, and relished the opportunity that BIM provided to continue that work.

For these practitioners, because their enthusiasm for BIM was based around the opportunity to teach others, their personal development in BIM ability was often driven by wanting to understand more about the technology and process in order to teach others more effectively. In some cases, however, the drive to understand all of the various roles and requirements in the BIM environment came more from a personal quest for knowledge; this professional identity has been labelled the *Inquirer*. Very few of the practitioners stepped into well-defined roles or established BIM practice. As a consequence, they had to be largely self-directed in developing their capabilities and finding sources of information to learn from. For practitioners who fit the inquirer type, this opportunity to drive their own learning within an embryonic field was a central attraction of the role. They were often passionate, self-declared 'BIM evangelists', who took every opportunity to learn and share their knowledge.

> It's interesting stuff, so you're driven to learn, driven to talk to people, to meet with different software vendors, to meet with different industry peers, just different, just cross-pollination I suppose, with respect to exposure... I'm the sort of person who, you need to be personally

> interested in something for it to be worthwhile, so you want to invest your time and your efforts in it, and then you look for opportunities where you can start.
>
> *Interview 15—Australia, Property development and management company*

Understanding BIM practice for practitioners in this type is often about developing a better knowledge of wider industry connections and the roles played by others in the BIM process. For some practitioners, however, BIM technology, roles and practice may be seen as a current interest that is just one element of a wider quest for knowledge and new ideas. These have been labelled the *Innovator*. Ahn et al. (2016) identified that BIM experts often go beyond the current implementation role to a more research and development focus to identify potential advancements in practice that could be adopted by their project team or organisation. This was evident in some of the companies with more advanced BIM practice, in that the BIM practitioners interviewed had, in addition to their BIM role, a specific responsibility to identify and evaluate potential applications of new technology that would benefit the company or its clients. As one interviewee noted, this was not necessarily an aspect of BIM practice, but "BIM is the easy term, people understand that", whereas the role was much broader in scope:

> …trying to figure out, what are those next things that are coming down the pipe from industry, what are our competitors doing, what are we doing in the company that need to get bubbled up to the greater good. *Interview 73—USA, Multi-disciplinary consultancy*

Specific innovations described by participants included lean construction, supply chain management, big data, use of drones and virtual reality. If the same questions were asked now, just three or four years later, that list is likely to be far more extensive as ideas around digital construction have become more widely disseminated. In this respect, BIM can be seen as an enabler, opening the door to further applications and innovations. Many of the BIM practitioners expressed keen interest in technology as a central driver to their involvement in practice, and so these same people and characteristics can be assumed to be driving the development of roles and practice in digital construction.

5. Identity and practice

Many of the practitioners expressed a feeling of constant struggle to carve out the time required to adequately perform their BIM role. Because they were identified as BIM specialists, they were expected to develop and disseminate BIM skills as well as implement practice standards and processes for appropriate BIM use within their organisation. Set against this was the need for them to be 'hands-on' with BIM in project delivery, commonly because of a lack of other staff with the necessary BIM skills. For many, this meant their BIM role was less about management of the virtual project within the BIM framework, which they saw as a priority, and more about producing the deliverables for the physical project which was a priority to other project participants. The necessary reframing of processes and relationships to enable effective BIM use was thus constantly undermined by a lack of resourcing and the prioritisation of traditional project roles over performing a BIM identity. Despite BIM practitioners' assertions about the value of their strategic and process-centred BIM activities to their organisation and project teams, the cues they received from their environment frequently relegated BIM to a technical delivery role. In such a situation, the practitioner's BIM identity is threatened by a fundamental misalignment between the individual's assertion of the importance of BIM and the changes it brings, against existing work practices and the established institutional logic. The overriding influence in the conflict between establishing longer term, more fundamental standards, and immediate project needs, is the established industry norm that project requirements take precedence over other factors (Jacobsson & Linderoth, 2010). This jeopardises the progression necessary for roles to develop through the professional life cycle, to a point where they become more defined and practice becomes embedded.

From the practitioners' perspective, despite the attractions, a BIM career was seen as an uncertain prospect. Many of the practitioners expressed apprehension that their career trajectory in their organisation was potentially limited because of the path they had taken. Very few senior management positions exist for those with a technical focus, and strategic BIM roles were considered by many to be short-term positions, necessary during the adoption phase of BIM but redundant once BIM practice is embedded. As a result, most saw their current career path as a dead end. This view mirrors that asserted by Akintola, Venkatachalam & Root (2017), that BIM practitioners are only likely to have a longer-term role as technical support, rather than as a core professional role in organisations and project teams. From this perspective, BIM roles will reduce in importance and scope as BIM becomes more embedded in the industry. However, this treats BIM as a complete technology in itself, and BIM integration as a destination rather than a process. It overlooks the ongoing development of BIM and its place as a component of digital construction. Supporting professional identities that include BIM or digital construction allows practitioners to participate in the evolution of digital practice in the industry.

The professional life cycle model suggests that a variety of roles are required that encompass different levels of focus. Scott (2008) distinguishes between different types of professional authority, with three categories identified, namely creative professionals, who generate new frameworks and rules of practice that underpin the work of others in their field; carrier professionals who transmit and interpret the profession's ways of working to others, and "must adapt and translate their messages to fit specific recipients and varying local circumstances"; and clinical professionals who are involved in actively applying the principles and frameworks of their profession to the problems of their clients or environment. Scott further makes the point that every profession has a set of parallel or subsidiary semi-professional roles that operate under the authority of the core professionals. From this perspective, it appears that the BIM profession is following a similar pattern to established professional groups. Not all BIM roles are necessarily held by BIM professionals, but represent a core of BIM professional roles, with individuals acting as creators, carriers or appliers within their domain of specialised expertise and knowledge, supported by technicians or associated roles that enable them to deliver the professional services their clients (whether in-house or external) require. This way of viewing professional roles aligns with the professional life cycle, with different types of role filled by practitioners with varying interests and levels of expertise, according to the needs of the role. Practitioners whose identity is invested in innovation and inquiry are likely to be less interested in validation and formalisation, whereas interpreters and instructors will be strong in those areas. Those who are more aligned to implementation have an obvious role within the commodification stage.

6. Identity and industry maturity

Digital construction is still very much a concept under development. Even when focusing specifically on BIM, which may be considered a relatively mature application, it is clear that practice is not uniform internationally or even nationally, despite ongoing efforts from governments and industry leaders. Change has yet to penetrate lagging industry sectors in developed BIM environments (Ganah & John, 2014), and many less advanced construction markets still exist, particularly in developing countries (Bui, Merschbrock & Munkvold, 2016). The five countries included in this research were selected because of the different levels of BIM maturity that they are widely perceived to represent. However, very little variation was evident in the views expressed by practitioners. Many compared their own country's practice with other BIM environments, and were cynical about the progress claimed.

> There's a heck of a lot of good people talking about this sort of stuff, but we've done a lot of global tours and we've been surprised by how little – there's pockets of areas where people have done it, but it's more sales pitch than substance. *Interview 37—NZ, Engineering consultancy*

Although there have been many surveys and evaluations published which show the rapid progress of BIM adoption in different international contexts, and within different disciplines and project environment types, practitioners were similarly dubious regarding how accurately such reports reflect the reality of practice. Practitioners in all countries considered local practice to be much more uneven and poorly developed than the various surveys represent, and as a result they were skeptical about the reported advances in other countries as well. It was widely believed that there is as much disparity in practice within each country as there is between countries, even in the environments that are perceived to be leading the way in BIM adoption internationally. This is reflected in the range of practitioner identities expressed, even within companies and countries that are held up as examples of best practice.

Balanced and objective representation of roles and responsibilities is necessary to allow practitioners to make an informed choice to move into a career in digital construction. Confusion around practice and progress acts as a disincentive to embracing a professional identity that centres on digital application or innovation. Practitioners who might otherwise be interested in moving into digital practice may be averse to do so when it is unclear how the industry is responding even to BIM and more widely recognized applications. The lack of transparency about the scale of the challenge involved may prove off-putting and is harmful to all involved if decisions are made based on biased or incomplete information. An overly rosy view is likely to give way to cynicism, when touted changes turn out to be illusory, or to disillusionment, when expected transformations do not eventuate. An unduly negative view is likely to deter practitioners from engaging if progress is not seen to be taking place.

7. Conclusions

For most of the practitioners interviewed, BIM was a central part of their professional identity, and they took pride in their involvement in BIM practice. A range of identity performance preferences were identified, comprising implementer, interpreter, instructor, inquirer and innovator identities. This variety indicates the range of interests and abilities expressed by BIM practitioners, and thus the diverse types of roles they were comfortable in engaging with. Practitioners' identity preferences were not always well aligned with the organisational and project roles they were expected to fill, making it difficult to achieve their goals. Most practitioners were not wholehearted in embracing a BIM identity, but were quick to assert their ongoing involvement with traditional roles and skills. There is an apparent stigma to being perceived as a BIM practitioner that some feared may limit their progression or opportunities in their organisation. The lack of a clear career path for BIM practitioners is a strong influence in this reluctance to fully accept a BIM role. The range of roles in which practitioners are expected to be actively involved also contributes. The requirement of balancing involvement in strategic, process and technical activities across organisational and project layers of responsibility leads to conflicting priorities and responsibilities.

The life cycle model of professional development provides a framework that may prove useful in structuring BIM practice and further development into digital construction, as a professional pathway. This model provides a representation of the profession that encompasses different levels of professional activity from innovation, through validation and formalization, to implementation as standard practice. It allows for definition of a range of professional roles that contribute to the overall progression of practice, and incorporates views that allow for the full range of identity and performance preferences expressed by practitioners. Connecting this, or a similar framework, to the current efforts in curriculum development and certification of BIM professionals would provide a certainty and status for BIM practitioners that is currently lacking. The diffusion and maturation process for BIM professional roles is clearly still ongoing, while at the same time new digital technologies are being adapted and adopted for use in construction. The speed at which practice and expectations are evolving means that capabilities of individuals and companies, as well as the industry in general, must be designed and redesigned to remain relevant and effective. BIM is not the end point of the current drive for industry improvement, and it is necessary to continue the cycle to develop and establish professional roles, knowledge and skills through and beyond current best practice. By using the life cycle model to provide an overview of the professional continuum, the efforts of practitioners can be fitted to their strengths in the interest of both practitioner and practice.

References

Ahn, Y.H., Kwak, Y.H., & Suk, S.J. (2016). Contractors' transformation strategies for adopting building information modeling. *Journal of Management in Engineering*, 32(1). doi:10.1061/(ASCE)ME.1943-5479.0000390

Akintola, A., Venkatachalam, S., & Root, D. (2017). New BIM roles' legitimacy and changing power dynamics on BIM-enabled projects. *Journal of Construction Engineering and Management*, 143(9), 04017066. doi:10.1061/(ASCE)CO.1943-7862.0001366

Alvesson, M. (2011). *Interpreting interviews*. Sage Publications Ltd, London

Andersen, L. P., Karlsen, I. L., Kines, P., Joensson, T., & Nielsen, K. J. (2015). Social identity in the construction industry: implications for safety perception and behaviour. *Construction Management and Economics*, 33(8), 640-652. doi:10.1080/01446193.2015.1087645

Bosch-Sijtsema, P. M., Gluch, P., & Sezer, A. A. (2019). Professional development of the BIM actor role. *Automation in Construction*, *97*, 44-51. doi:10.1080/15623599.2019.1602585

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), 77-101. doi: 10.1191/1478088706qp063oa

Brown, A.D., & Phua, F.T.T. (2011). Subjectively construed identities and discourse: towards a research agenda for construction management. *Construction Management and Economics*, 29(1), 83-95. doi:10.1080/01446193.2010.531028

Bui, N., Merschbrock, C., & Munkvold, B.E. (2016). A review of Building Information Modelling for construction in developing countries. *Procedia Engineering*, 164, 487-494. doi:10.1016/j.proeng.2016.11.649

Clandinin, D.J., & Connelly, F.M. (2000). *Narrative inquiry: Experience and story in qualitative research*. San Francisco: Jossey-Bass.

Davies, K., Wilkinson, S. & McMeel, D. (2017a). A review of specialist role definitions in BIM guides and standards. *Journal of Information Technology in Construction (ITcon)*, Vol. 22, pg. 185-203, http://www.itcon.org/2017/10

Davies, K., McMeel, D. J., & Wilkinson, S. (2017b). Making friends with Frankenstein: hybrid practice in BIM. *Engineering, Construction and Architectural Management*, 24(1), 78-93. doi:10.1108/ECAM-04-2015-0061

Ganah, A. A., & John, G. A. (2014). Achieving Level 2 BIM by 2016 in the UK. *Computing in Civil and Building Engineering*, 143-150. doi:10.1061/9780784413616.019

Gluch, P. (2009). Unfolding roles and identities of professionals in construction projects: exploring the informality of practices. *Construction Management and Economics*, 27(10), 959-968. doi:10.1080/01446190903179728

Golden-Biddle, K., & Locke, K. (2007). *Composing qualitative research* (2nd ed.). Thousand Oaks, CA: Sage.

Jacobsson, M., & Linderoth, H.C. (2010). The influence of contextual elements, actors' frames of reference, and technology on the adoption and use of ICT in construction projects: a Swedish case study. *Construction Management and Economics, 28*(1), 13-23. doi:10.1080/01446190903406154

Lawrence, B., Zhang, J.J., & Heineke, J. (2016). A life-cycle perspective of professionalism in services. *Journal of Operations Management, 42,* 25-38. doi:10.1016/j.jom.2016.03.003

Lepisto, D.A., Crosina, E., & Pratt, M.G. (2015). Identity work within and beyond the professions: Toward a theoretical integration and extension. In A. Desilva and M. Aparicio (Eds.), *International handbook of professional identities*, 11-37. Rosemead, CA: Scientific & Academic Publishing.

Miettinen, R., & Paavola, S. (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. *Automation in Construction, 43*, 84–91. doi:10.1016/j.autcon.2014.03.009

Poirier, E., Forgues, D., & Staub-French, S. (2016). Collaboration through innovation: implications for expertise in the AEC sector. *Construction Management and Economics*, 34(11), 769-789. doi:10.1080/01446193.2016.1206660

Rogers, D. (2019). A visit to the Oracle: Reviewing the state of construction industry digitalisation, *Construction Research and Innovation*, 10:1, 11-14, doi:10.1080/20450249.2019.1587238

Saldaña, J. (2013). *The coding manual for qualitative researchers*, 2nd edition. London: Sage.

Scott, W. R. (2008). Lords of the dance: Professionals as institutional agents. *Organization Studies*, 29(2), 219-238. doi:10.1177/0170840607088151

Stuckey, H.L. (2015). The second step in data analysis: Coding qualitative research data. *Journal of Social Health and Diabetes*, 3(1), 7. Retrieved from http://www.joshd.net/text.asp?2015/3/1/7/140875

Styhre, A. (2012). Identification work in the construction industry: Ideal selves, project performance, and disidentification. *Leadership & Organisation Development Journal*, *33*(7), 632-645. doi:10.1108/01437731211265223

Succar, B., Sher, W., & Williams, A. (2013). An integrated approach to BIM competency assessment, acquisition and application. *Automation in Construction*, *35*, 174–189. doi:10.1016/j.autcon.2013.05.016

Uhm, M., Lee, G., & Jeon, B. (2017). An analysis of BIM jobs and competencies based on the use of terms in the industry. *Automation in Construction*, 81, 67-98. doi:10.1016/j.autcon.2017.06.002

Integrating Building Information Modelling (BIM) and System Dynamics Approaches to Decrease Cost Overrun in Mass Housing Projects

Moslem Sheikhkhoshkar[1,*], Mostafa Mir[2], Farzad Pour Rahimian[1], Bimal Kumar[3]
[1]School of Science Engineering and Design, Teesside University, Middleborough, UK
[2] Deakin University, Australia
[3] Northumbria University, Newcastle UK
* email: msheikhkhoshkar@gmail.com

Abstract

Cost is one of the most important criteria for evaluating the success of a construction project. Estimating construction costs is an increasing necessity for accurate budgeting and effective allocation of funding since the lack of accuracy in cost estimation could increase the risk of cost overrun. One of the major difficulties in estimating the project cost accurately is the changes occurred in materials price during the project completion period. The aim of this study was to develop a systematic multi-objective knowledge-based approach for estimating the project cost with more accuracy and decrease the risk of cost overrun at the conceptual stage. System development methodology comprises a framework to deploy a system that automatically generates conceptual cost estimates by integrating System Dynamics (SD) with Building Information Modelling (BIM) through an external data interchange protocol in synchrony with interoperability standards. The SD module is used to predict the material price during the project completion period whilst using BIM helps enter detailed properties of the materials as well as the quantity take offs. Deployment of the proposed system will minimise the subjectivity whilst making investment decisions related to building projects and assisting designers and cost engineers to obtain results in an integrated quantitative, qualitative, and dynamic manner. The results show that the model can predict the price of the material with a reliable accuracy and they are anticipated to be of major significance to owners, designers, and construction managers. An application of an actual mass construction project is presented in order to illustrate the usefulness and capabilities of the developed approaches.

Keywords: Building Information Modelling, System Dynamics, Cost Overruns, Multi-objective Optimisation, Expert System

1. Background of the study

The performance of every construction project is evaluated by three criteria, namely time, cost and quality (Khanzadi et al., 2018). It is an aim to complete construction projects at the estimated budget. However, cost estimation should be precise enough to meet the assumed budget. Cost estimation is one of the most important phases of the project planning (Hwang et al., 2012). The estimated cost is generally computed based on the cost of project determinants including construction materials, labour, equipment, and method (Myers, 2016). Yet, numerous other factors can affect construction cost such as the project locality, type, construction duration, scheduling (Rafiei & Adeli, 2018). Furthermore, the fluctuation of economic variables and indexes, can also cause variation in costs, especially in an unstable economic environment (Jafarzadeh et al., 2013; Rafiei & Adeli, 2015). As the material cost accounts for a significant portion of the construction cost, an accurate prediction of raw materials price is important for an accurate prediction of the total cost (Alvanchi *et al.*, 2011). Identifying cost factors has always been of the interest of construction researchers (Alvanchi *et al.*, 2011; Issa, 2000). However, there are limited studies, which concentrated on predicting the materials cost and applying it in a real construction project. Marzouk and Amin (2013) presented a system that utilises fuzzy logic to identify construction materials that are most sensitive to the price changes. This approach is used to modify the contract price with an attempt to predict the amount of future change in the price of materials by using neural networks technique. OuYang *et al.* (2013) proposed a back propagation neural network method to predict the value of the material price in construction projects. Hassan *et al.* (2013) measured the historical volatility of the prices of three key construction materials, namely steel, cement, and lumber. They assessed the degree of risk involving construction cost caused by material price fluctuation. Due to the dynamic changes on the value of the materials' price during the construction project, as well as the assignment of the budget to the work packages according to the initial cost estimation, cost overrun would be considered as a common challenge in the construction projects (Doloi, 2012).

There are many factors that influence material cost in the construction industry. Some studies introduced factors, taking into account the condition of the market or seasonal condition on the material price. However, identifying the quantitative relationship between these factors as well as collecting data by considering these factors are not easily possible. According to estimators in construction companies, the material price trends to be forecasted have the following characteristics: 1) no seasonal variations can be found in most material price time-series data; 2) material prices tend to remain steady even if they increase once in a recessionary period; and 3) extensive data collection is required to make a single prediction (Hwang *et al.*, 2012; Williams, 1994). Therefore, factors that consider the general conditions of the market are needed as primary indicators to study material price. Issa (2000) introduced seven factors which have impact on construction material price: number of privately-owned single-family housing which starts from the Bureau of the Census of the US Department of Commerce; prime interest rate from the US Federal Reserve Board; 30 years home mortgage interest rate from the Federal Home Mortgage Loan Corporation; US Consumer Price Index from the US Department of Labour; 30 years US Treasury Bond from the US Federal Reserve Board; the Dow Jones Industrial Average; and past price for that material.

In the recent years, Building Information Modelling (BIM) has emerged as a comprehensive concept of process and tools which integrates all projects required data and information (Eastman *et al.*, 2011). BIM offers the capability to generate take-offs, counts, and measurements directly from a model. The major application of applying BIM based tools to estimate project costs occurs during the quantity take off stage (Eastman *et al.*, 2011). BIM has been utilised in cost estimation, with research revealing that it is more efficient than the manual cost estimation and leads to project cost reduction (Azhar, 2011). Ma *et al.* (2010) proposed a prototype for BIM based construction cost estimating (CCE) software that used the Chinese standards. Hartmann *et al.* (2012) described the implementation of BIM-based tools to support the activities of the estimating department of a construction company on a large infrastructure project. Ok *et al.* (2009) established the methodology of property information modelling that could support the quantity take-off of a structural element for reflecting the cost estimate feature of a public building.

System Dynamics (SD) is a method, which is originally introduced by Forrester (1958), and concentrates on dynamic complexity (Lättilä *et al.*, 2010). SD represents the resources and dynamics within a system as a set of stocks and the flows between them. SD is useful for understanding the behaviour of complex systems and the effects of causal factors over time (Mostafavi *et al.*, 2012). There, are few studies utilising SD model and BIM to improve the performance of their systems. Bank *et al.* (2011) developed a decision-making framework for the sustainable design of buildings with a BIM tool. They integrated an SD model into BIM design process as a decision-making tool to improve measurement, prediction, and optimisation of sustainable building material performance.

This research proposes a new approach to the integration of SD and BIM for material cost estimation in construction projects. The solution is to develop a dynamic system, which can predict the value of the materials' price during the project running period and insert this value into the cost estimation system to provide more precise and dynamic cost estimation. Therefore, in this study, a BIM-SD method for calculating the accurate estimate of material cost is proposed to address the problems of budgetary inaccuracy, the lack of comprehensive, and the existence of serious waste of auxiliary materials during the main construction phase of mass housing construction. The successful implementation of such a methodology represents a tool, which helps project managers to predict the materials' cost more precisely and enclose the cost estimation more accurate and close to reality.

2. Methodology

The proposed model simplifies the process of building costs estimation and evaluates numerous factors, which have direct impacts on the cost of building materials. Because the material price changes in different areas, generating a general model to predict the material price as well as collecting data from different areas is not easy. However, the Producer Price Index (PPI) can be used as a criterion to consider the past price of the construction material. By predicting PPI from the provided data and by using the PPI formula, the material price can be obtained. According to USA Department of Labour/ Bureau of Labour Statistics: “Producer price index measures the average change in prices received by domestic producers for their output and it measures price changes that are received by mining, manufacturing, services, and construction providers. PPIs are based on a monthly sample of over 100,000 prices." PPI has a baseline starting from 1986. Bureau of Labour Statistics releases the PPI periodically to help industries to adjust the prices in their contracts.

The required data for the SD model are obtained from the specified sources after the names of the factors and the quantitative model created using a regression model. Because of the dynamics exists in the economics and the market, the value of the factors, which are affecting the material price change during the project period. The value of the factors changes during the construction process as well. Thus, assuming the constant values for the factors may decrease the accuracy of the output. Prediction of these factors requires economical calculation as well as an expertise in the economic and market condition. This study uses the predictions presented in the reliable economical websites to obtain more accurate results from the SD model. The predicted values for the introduced factors affecting the material price are provided from the website (www.forecasts.org) as an expert website in the prediction of economic factors. This website uses Time Delay Neural Network (TDNN) and Singular Spectrum Analysis (SSA) to predict the economic factors. Time Delay Neural Network is a certain type of neural network which works with time series data. SSA is a spectral estimation method used to decompose a time series into subcomponents such as trend, cyclical components, and noise. The value of material price can be calculated from the PPI. The current PPI, base material price and base PPI are needed to obtain the current value of material price. The base material price and base PPI are the material price and PPI at a base time. These values can be obtained from the historical data. Equation 1 represents the method on how the material price can be calculated.

$$Material\ Price = \text{Base material price} \times \left(\frac{Current\ PPI}{Base\ PPI}\right) \quad (1)$$

The SD-BIM integration model consists of four main phases: the SD, BIM, Database and the Dynamo modules. Each of the main phases has a significant role in the information exchange through the integrated model. Following are the explanations on the role of each section in the integration process making with their connections, which create the integration model. Figure 2 shows the main parts of the integrated model and their connections.

2.1 Phase 1. Developing SD Model

The aim of the SD model is to predict the value of the material price during the project duration. The prediction would be based on the regression model, which is provided by the historical data as well as the value of the factors that influences material price in the project duration, which is provided from the reliable economic prediction websites. The SD model has been developed based on seven factors that extract from (Issa, 2000) in the AnyLogic© simulation tool. Figure 1 shows the SD qualitative model of the material price.

2.1 Phase 2. Developing BIM Model

The second phase is focus on developing a BIM model for selected case study. The first step is to design and implement a 3D modelling and their associated keynotes for components commonly used in building projects. The BIM model where project cost estimation takes place and the initial value of the material cost and project duration would be inserted into the model. Also, the BIM model is the host for the average material price, which is taken from the database. This estimated price is calculated for the project duration, as shown in Figure 2. The quantity take-off and cost estimation for the whole project would be extracted from the BIM tool. Then the BIM model estimates the total cost based on the quantity take-off as well as the new material price in the BIM model.

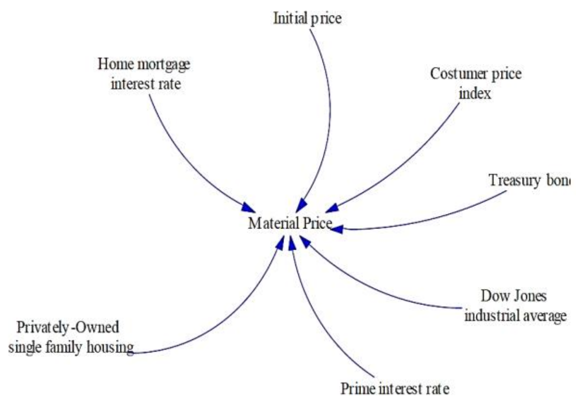


Figure 1: SD qualitative model

2.2 Phase 3. Developing Database

Due to major role that information play in BIM works, every BIM project needs a comprehensive database, which encompasses all materials' details. Hence, the materials used in each design should be identified physically and practically (Jalaei & Jrade, 2014). The integrated proposed model needs a database to interfere between the SD and BIM models since the tools that are used to develop the SD and BIM models cannot be connected directly. The data, which is going to be transferred between the models would be recorded in an Excel-based environment as the database. The models will use the information saved in the database when needed.

2.3 Phase 4: Using Dynamo

The automation process for information transfer between the Excel as the database and the BIM model is done by using Dynamo, which is the platform linked to the BIM tool (i.e. Autodesk Revit©) as an add-in. The developed algorithm in dynamo is used to enact as a bridge between Excel environment as the database and Revit as the BIM tool, which is illustrated in Figure 2. Dynamo uses visual programming to link finished code blocks in the way that they form a logical unit and perform certain tasks. The initial price of the material and project duration, which has been saved in the BIM environment would be sent out from the Revit to the Dynamo. Dynamo passes out the value of initial cost and project duration to the excel file, which stores these data in the database. The SD model reads the value of initial cost from the database and inserts it as a factor, which is used to predict the value of the material price in future months. At this stage, the SD model starts to simulate the value of material price in future months and generates the material price for every month. The monthly value of the material price that has been predicted by the SD model is inserted into the database. This monthly material price should be converted into one value since Revit cannot accept several values for the price of a specific material. Thus, the number of the months, which the project will take as the project duration will be sent out from the project duration section of the BIM tool (Revit) to the Database. In the Database, the average of the material price through the project duration would be calculated and the average price would be released to the Dynamo. The Dynamo then would change the value of the material price in the material properties box in the Revit. The BIM model will use this value as the value for cost estimation prices. Figure 2 shows the architecture of integration of SD and BIM model.

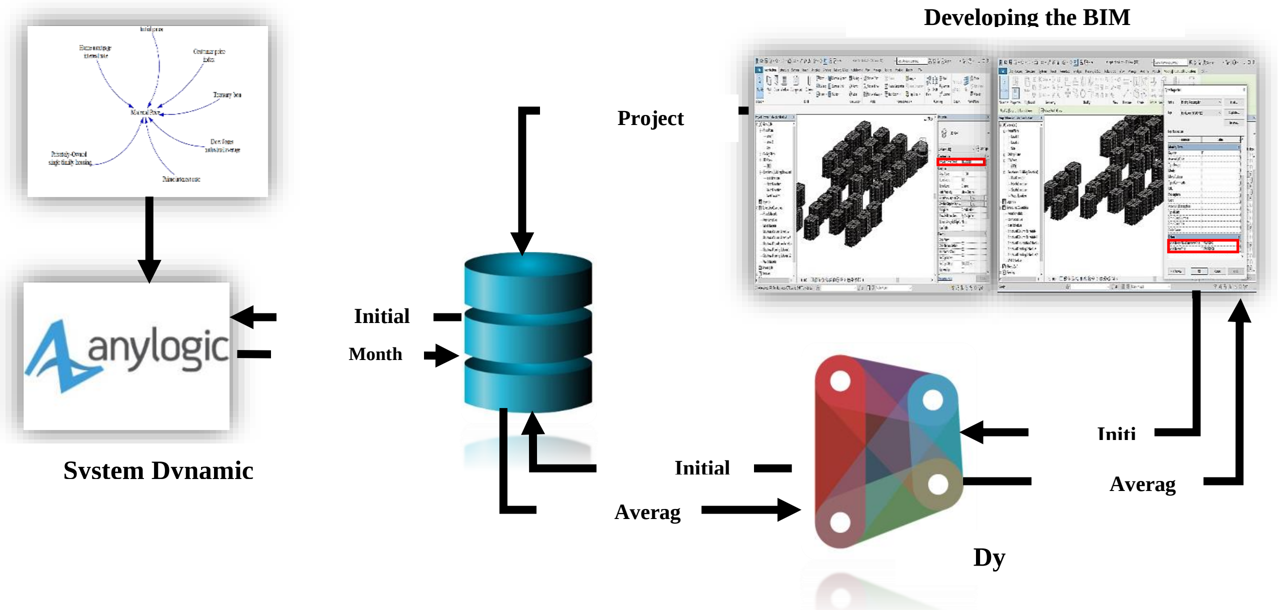


Figure 2: The structure of integration of SD and BIM

3. Model Implementation

This section describes the process of implementing the proposed integration of SD and BIM using data of a real construction project. The case study is a mass housing construction of a residential complex, located at British Columbia (BC), Canada. The residential complex consists of 35 stories blocks. There are many materials, which have been used for the construction project due to the limitations of the research, the cost for two major structural elements of this building project (i.e. freshly mixed concrete (28 MPa) and steel rebar [#8 to #18]) have been studied. However, implementation of the proposed model for these materials shows the ability and capability of the proposed model to be applied to all the materials that are used in the construction process. According to quantity take off from the BIM model of the case study, it would be needed 905.12 m^3 of freshly mixed concrete (28 MPa) as well as the 84.16 tons of steel rebar [#8 to #18] to complete each block of the project. Because the PPI value for every material is different, the quantitative model in the SD is different for every material as well. Thus, according to the historical data for the PPI for freshly mixed concrete and the steel rebar, a unique SD quantitative model is developed for each material. The BIM model of the mass housing construction has been developed and the initial cost of every material used in the construction process has been applied to the BIM model by the user. Figure 3 shows the snapshot of the case study, which is taken from the BIM model.

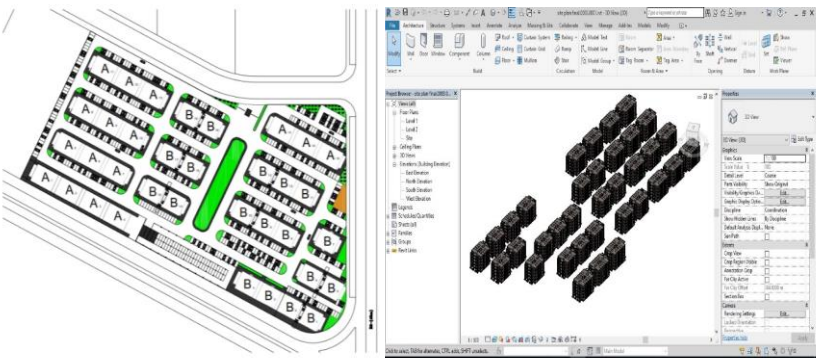


Figure 3: BIM model for the case study

The initial price for fresh mixed concrete and steel rebar is inserted into the Revit model. These values are transferred into the database using Dynamo, which is shown in Figure 4. Then, the SD model reads the initial cost of every material and insert it into the SD model associated with that material. The SD model simulates the price for every material and predicts the price for fresh mixed concrete and steel rebar on a monthly basis. The results of the SD model will be transferred to the Database. Figure 5 shows the linking between SD model and the database with Java programming interface code.

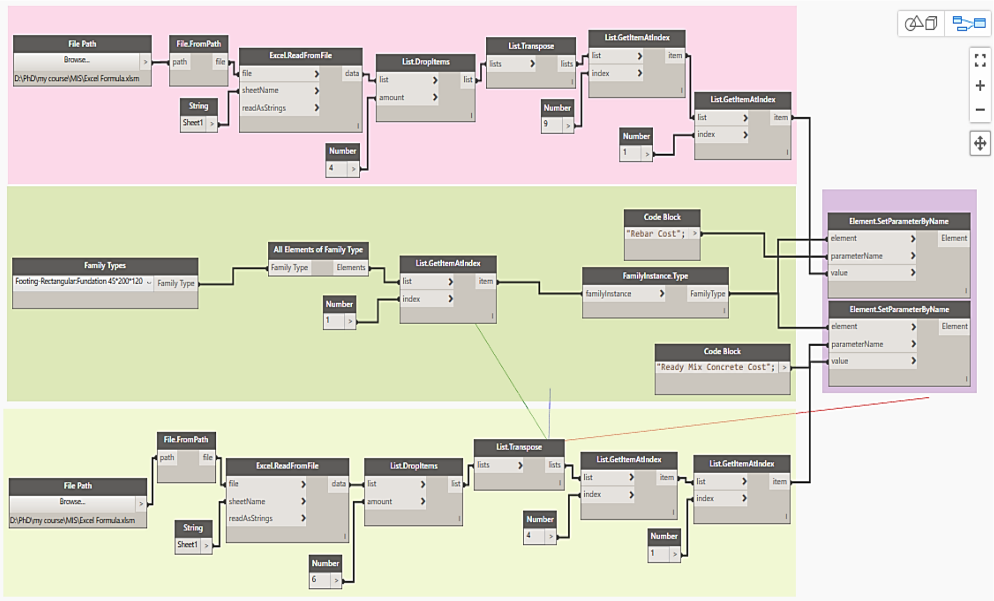


Figure 4: a Mutual connection between the BIM model and the Database using Dynamo

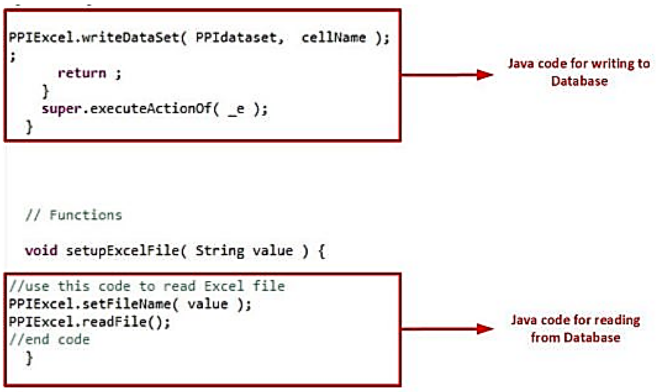


Figure 5: Programmed information flow between SD and Database

The construction programme is also transferred from Revit to the Database. Then, the average of quantities for the fresh mixed concrete and steel rebar in the project duration is calculated in the Database, which is illustrated in Figure 6. The average material price is transferred from the database into Revit by Dynamo, as previously shown in Figure 4. The value of the material price for each material is changed in the material parameter toolbox in Revit according to the new material price values as shown in Figure 8. The new material prices are used by BIM to estimate the project cost. The results of the model show the effectiveness of the model in the process of cost estimation. In this section, first, the reliability of the SD model is illustrated, then the effectiveness of integrating SD as a simulation tool into BIM is depicted in the represented case study

.

Time	Ready Mix Concrete Cost	Project Time (Month)	Ready Mix Concrete Cost in Project Time	Project Time (day)
1	164.0258609	1	164.0258609	480
2	164.0258609	2	164.0258609	Project Time (Month)
3	164.6636019	3	164.6636019	16
4	165.325195	4	165.325195	Initial Ready Mix Concrete Cost
5	167.0600292	5	167.0600292	162.67
6	167.4894565	6	167.4894565	Average Ready Mix Concrete Cost in Project time
7	169.3125071	7	169.3125071	168.7642534
8	169.012527	8	169.012527	
9	170.0539897	9	170.0539897	
10	170.1698386	10	170.1698386	
11	170.4003581	11	170.4003581	
12	170.837728	12	170.837728	
13	170.6327751	13	170.6327751	
14	171.781694	14	171.781694	
15	172.1172306	15	172.1172306	
16	173.3194025	16	173.3194025	
17	173.3374376	17	0	
18	173.5515855	18	0	
19	173.8349593	19	0	
20	174.7300404	20	0	
21	175.2184299	21	0	

Time	Rebar Cost	Project Time (Month)	Rebar Cost in Project time	Project Time (Month)
1	1178.518176	1	1178.518176	16
2	1173.93232	2	1173.93232	Initial Rebar Cost
3	1159.010583	3	1159.010583	1158.82
4	1151.253731	4	1151.253731	Average Rebar Cost in Project time
5	1174.913064	5	1174.913064	1134.988781
6	1138.168006	6	1138.168006	
7	1139.674143	7	1139.674143	
8	1131.104142	8	1131.104142	
9	1127.381306	9	1127.381306	
10	1123.506412	10	1123.506412	
11	1120.247668	11	1120.247668	
12	1131.969694	12	1131.969694	
13	1112.11572	13	1112.11572	
14	1111.232051	14	1111.232051	
15	1090.136072	15	1090.136072	
16	1096.657406	16	1096.657406	
17	1151.253731	17	0	
18	1174.913064	18	0	
19	1138.168006	19	0	
20	1139.674143	20	0	
21	1131.104142	21	0	

Figure 6. The outputs of the SD model exported into database and calculation of average cost for ready mixed concrete and Rebar steel

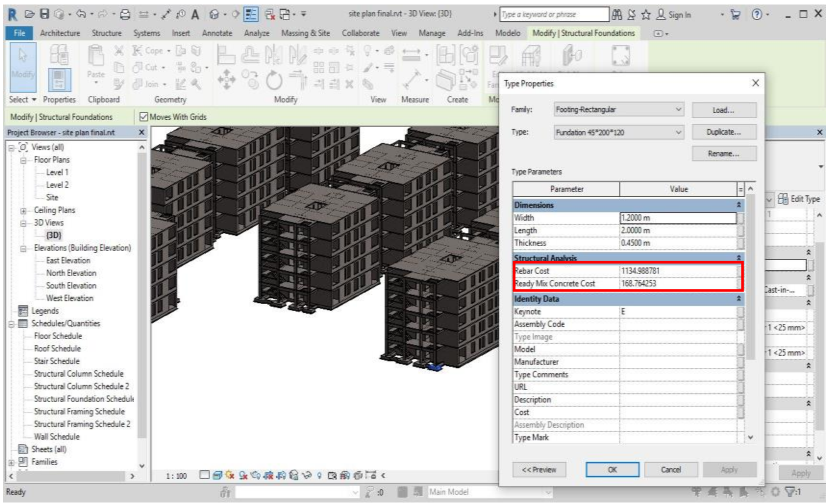


Figure 8: Ready-mixed concrete and rebar cost in the BIM

4. Validation of the SD model

This study uses the RSMeans as the main source for validation of the outputs of the SD model. RSMeans is a database that provides accurate and up to date cost for different materials and operations in North America to help contractors, owners, architects, engineers, and others in estimating projects cost more accurately. The reason for selecting RSMeans as a validation source is that the factors, which affect the value of material cost in this study convey the information about the North America market condition. Material price in RSMeans is presented based on every quarter of the year and the SD model in this study predicts the material price monthly. The average of the material price in three months, which is obtained from SD model would be used as the quarterly material price value to be compared to the output of the RSMeans. Table 1 show the values of the material price from the SD model and RSMeans for last quarter of 2017 as well as the first quarter of 2018. Several dollars difference for every ton or cubic meter of the material between the output of the SD model and the RSMeans depicts the reliable performance of the SD model. This reliability will be shown at the cost estimation in the next section.

Table 1: Predicted Ready-mixed concrete price and steel rebar price by RSMeans and the SD model

Ready mixed concrete (28 MPa) price			steel bar (#8-#18) price	
Data Source	**2017 Quarter 4**	**2018 Quarter 1**	**2017 Quarter 4**	**2018 Quarter 1**
RSMeans	163.33 $	162.83 $	1082.88 $	1065.02 $
SD model	164.238 $	166.625 $	1083.353 $	1069.303 $

Table 3 provides the simulated material price by the SD model for the rest of the project duration to be considered into cost estimation. According to the values that are provided from the forecasting website for the involved factors in the SD model, the SD model is adjusted to predict the material price for the duration of the project selected as the case study. Therefore, the maximum reliable output of the SD model to predict the material price is the first month of 2019.

Table 3: Predicted material price by the SD model for the future months

Month of the project	4.2018	5.2018	6.2018	7.2018	8.2018	9.2018	10.2018	11.2018	12.2018	01.2019
Mixed concrete price ($/m3)	169.3	169	170	170.17	170.4	170.8	170.6	171.78	172.1	173.32
Steel rebar price ($/ ton)	1139.67	1131.1	1127.38	1123.5	1120.2	1132	1112.1	1111.2	1090.1	1096.7

According to the conducted quantity take-off from the BIM model of the case study, it would be estimated about 905.12 m^3 fresh mixed concrete (28 MPa) and 84.16 tons steel rebar (#8 to #18) to complete each block of the project. Furthermore, the quantity of the material, which will be used for the whole of the project are 31,679.2 m^3 and 2,945.6 tons of freshly mixed concrete (28 MPa) and Steel rebar (#8 to #18) respectively. According to the Table 4, the initial cost for freshly mixed concrete (28 MPa) is 162.67 $\$/m^3$ as well as 1139.43 $/ton for the steel rebar (#8 to #18). While the SD-BIM model proposes 168.8$ m^3 and 1134.99 $/ton for freshly mixed concrete (28MPa) and steel rebar (#8 to #18) respectively. It can be seen that the material price for freshly mixed concrete is increasing, but the material price for steel rebar is decreasing. This trend has been shown in Tables 1, 2 and 3, which show a variation of the material cost at different quarters for the studied materials obtained from RSMeans and the proposed model.

Table 4. Quantity and cost of the materials

Material	Quantity of the material	Initial unit cost	Unit cost by the proposed model
Fresh mixed Concrete(28MPa)	31,679.2 m^3	162.67 $	168.8 $
Steel Rebar (#8-#18)	2,945.6 tons	1158.82 $	1134.99 $

Variations in the material price show their influence on the project cost during project completion time. Conventional cost estimation cannot track these variations accurately. Based on the conventional method for the project cost estimation, the cost value for one material equals the quantity of the material multiplied by the unit cost of that material. Therefore, according to the table 5, the estimated cost for the required fresh mixed concrete and steel rebar are 5,153,255.464 $ and 3,413,420.192 $ respectively. On the other hand, the cost estimation based on the material cost obtained from the proposed model are 5,347,448.96 $ and 3,343,226.54 $ for the needed fresh mixed concrete and steel rebar in turn. These results show that initial estimated cost of the concrete is lower than the actual cost, which the project will experience. Thus, the managers should consider 195,000 $ additional financial resources for providing enough freshly mixed concrete. Meanwhile, the initial steel rebar estimated cost is more than what the project will experience during the project completion duration. The reason is that the reduction in the cost of the steel rebar has not been considered in the conventional cost estimation while the proposed model could track the reduction and consider its impact on the cost estimation perfectly. Therefore, managers can save more than 70,000$ of their financial resources and reduce the estimated budget for the steel rebar.

Table 5. Conventional cost estimation versus cost estimation by the proposed model

Material	Initial cost estimation	Cost estimation by the proposed model
Fresh mixed Concrete(28MPa)	5,153,255.464 $	5,347,448.96 $
Steel Rebar (#8-#18)	3,413,420.192 $	3,343,226.54 $

5. Summary and Conclusions

Due to the changes on the value of the materials' price during the construction project as well as the assignment of the budget to the work packages according to the initial cost estimation, cost overrun would be considered as a common challenge in the construction projects. In addition, as became evident in the reviewed literature, despite the wide application of new technologies have utilized in the AEC industry, there are still inaccuracy cost estimation issues that causes project cost overruns. To address these issues, this paper has developed a workflow for the linking of data within a BIM to a SD model as an automated and integrated model that allows to a realistic predict of the material price and estimate the project cost. In view of this line, BIM is used to collect the material price for every item as well as the quantity take-off and cost estimation for the whole project. SD model is used to predict the value of the material price in the market. The material price is affected by numerous factors, which are included in the SD model as well as the predicted values for each factor that are used to increase the accuracy of the predicted material price. Information will be transferred between BIM and SD model mutually to develop an automated system to estimate the project cost. The model was verified using the construction cost data in RSMeans platform. Cost estimation variation of the proposed model were Several dollars difference with RSMean data base, thus demonstrating the effectiveness of the strategies employed in this research and the superiority of the proposed model.

The results show that the proposed method increases the estimation accuracy considerably. This accuracy assists construction managers to assess the proper budget for the projects and prevent the projects from cost overrun.

References

Alvanchi, A., Lee, S., & AbouRizk, S. (2011). Modeling framework and architecture of hybrid system dynamics and discrete event simulation for construction. Computer-Aided Civil and Infrastructure Engineering, 26(2), 77-91.

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. Leadership and management in engineering, 11(3), 241-252.

Bank, L. C., Thompson, B. P., & McCarthy, M. (2011). Decision-making tools for evaluating the impact of materials selection on the carbon footprint of buildings. Carbon Management, 2(4), 431-441.

Doloi, H. (2012). Cost overruns and failure in project management: Understanding the roles of key stakeholders in construction projects. Journal of Construction Engineering and Management, 139(3), 267-279.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors: John Wiley & Sons.

Forrester, J. W. (1958). Industrial Dynamics. A major breakthrough for decision makers. Harvard business review, 36(4), 37-66.

Hartmann, T., Van Meerveld, H., Vossebeld, N., & Adriaanse, A. (2012). Aligning building information model tools and construction management methods. Automation in Construction, 22, 605-613.

Hassan, M., Kandil, A., Senouci, A., & Al-Derham, H. (2013). Measuring construction materials price fluctuation risk.

Hwang, S., Park, M., Lee, H.-S., & Kim, H. (2012). Automated time-series cost forecasting system for construction materials. Journal of Construction Engineering and Management, 138(11), 1259-1269.

Issa, R. R. (2000). Application of artificial neural networks to predicting construction material prices. In Computing in Civil and Building Engineering (2000) (pp. 1129-1132).

Jafarzadeh, R., Ingham, J., Wilkinson, S., González, V., & Aghakouchak, A. (2013). Application of artificial neural network methodology for predicting seismic retrofit construction costs. Journal of Construction Engineering and Management, 140(2), 04013044.

Jalaei, F., & Jrade, A. (2014). Integrating building information modeling (BIM) and energy analysis tools with green building certification system to conceptually design sustainable buildings. Journal of Information Technology in Construction, 19, 494-519.

Khanzadi, M., Sheikhkhoshkar, M., & Banihashemi, S. (2018). BIM applications toward key performance indicators of construction projects in Iran. International Journal of Construction Management, 1-16.

Lättilä, L., Hilletofth, P., & Lin, B. (2010). Hybrid simulation models–when, why, how? Expert Systems with Applications, 37(12), 7969-7975.

Ma, Z., Zhang, X., Wu, S., Wei, Z., & Lou, Z. (2010). Framework design for BIM-based construction cost estimating software. Paper presented at the Proceedings of the CIB W.

Marzouk, M., & Amin, A. (2013). Predicting construction materials prices using fuzzy logic and neural networks. Journal of Construction Engineering and Management, 139(9), 1190-1198.

Mostafavi, A., Abraham, D., Delaurentis, D., Sinfield, J., & Queiroz, C. (2012). Innovation policy assessment for civil infrastructure system-of-systems. Paper presented at the Construction Research Congress 2012: Construction Challenges in a Flat World.

Myers, D. (2016). Construction economics: A new approach: Routledge.

Ok, J., Lee, M., & Jang, K. (2009). A study on the modeling of BIM property information in reflection of the public cost estimate distinctions. Proceeding of Korea Institute of Construction Engineering and Management, 772-777.

OuYang, H., Zhang, X., & Hu, C. (2013). Application Research on the Artificial Neural Network in the Building Materials Price Prediction. Paper presented at the 19th International Conference on Industrial Engineering and Engineering Management.

Rafiei, M. H., & Adeli, H. (2015). A novel machine learning model for estimation of sale prices of real estate units. Journal of Construction Engineering and Management, 142(2), 04015066.

Rafiei, M. H., & Adeli, H. (2018). Novel Machine-Learning Model for Estimating Construction Costs Considering Economic Variables and Indexes. Journal of Construction Engineering and Management, 144(12), 04018106.

Williams, T. P. (1994). Predicting changes in construction cost indexes using neural networks. Journal of Construction Engineering and Management, 120(2), 306-320.

BIM and its impact upon project success outcomes from a Facilities Management perspective

Duncan Rae[1], Dr. Barry Gledson[2, *] and Michelle Littlemore[2]
[1] Identity Consult, Sunderland, UK
[2] Faculty of Engineering and Environment, Northumbria University, UK
* Email: barry.gledson@northumbria.ac.uk

Abstract

The uptake of Building Information Modelling (BIM) has been increasing, but some of its promoted potential benefits have been slow to materialise. In particular, claims that BIM will revolutionise facilities management (FM) creating efficiencies in the whole-life of building operations have yet to be achieved on a wide scale, certainly in comparison to tangible progress made for the prior design and construction phases. To attempt to unravel the factors at play in the adoption of BIM during the operational phase, and in particular, understand if adoption by facilities managers (FMs) is lagging behind other disciplines, this study aims to understand if current BIM processes can ease the challenges in this area faced by facilities management project stakeholders. To do this, success from a facilities management viewpoint is considered and barriers to facilities management success are explored, with focused BIM use proposed as a solution to these barriers. Qualitative research was undertaken, using semi structured interviews to collect data from a non-probability sample of 7 project- and facilities- management practitioners. Key results from this study show that the main barrier to BIM adoption by facilities managers is software interoperability, with reports that facilities management systems are unable to easily import BIM data produced during the design and construction stages. Additionally, facilities managers were not treated as salient stakeholders by Project Managers, further negatively affecting facilities management project success outcomes. A 'resistance to change' was identified as another barrier, as facilities managers were sceptical of the ability of current BIM-enabled systems promoted as being FM compatible to be able to replicate their existing Computer Aided Facility Management (CAFM) legacy software and its user required capabilities. The results of this study highlight that more work is needed to ensure that BIM benefits the end user, as there was no reported use of BIM data for dedicated facilities management purposes. Further investigation into the challenges of interoperability could add significant value to this developing research area.

Keywords: BIM, CAFM, Facilities Management (FM)/Facilities Managers (FMs), Interoperability, Project Success, Stakeholders.

1. Introduction

Although Building Information Modelling (BIM) has been touted by industry bodies, government reports and academic research as a potential solution to many of the ailments afflicting the Architecture, Engineering and Construction (AEC) industry, some of the potential benefits have been slow to materialize. In particular, despite claims in research that BIM will revolutionise Facilities Management (FM) (Sabol, 2008; Arayici *et al*., 2012; Korpela *et al*., 2015) and significantly save money in building operations (Gallaher *et al*., 2004; Wijekoon *et al*., 2016), these aspirations have yet to be achieved on a wide scale, when compared to the progress made in recent years for the design and construction phases (Eadie *et al*., 2013; NBS; 2017; Ashworth & Tucker, 2017). The UK Government, in a first of two related Government Construction Strategies (2011), set a mandate for all centrally funded construction or infrastructure projects to use fully collaborative 3D BIM (or 'BIM level 2') by April 2016 (HM Government, 2011). This was followed in the GCS 2016-2020 by a commitment to "*embed and increase the use of digital technology, including Building Information Modelling (BIM) Level 2*". This approach has seemingly resulted in a strong uptake during the design stage, much slower uptake in the construction stage, and little use in the operational phase of a building (NBS, 2018). More recently, findings from the British Institute of Facilities Managements' (BIFM) survey have reinforced the claims that the FM industry are lagging behind other members of the construction industry (Ashworth & Tucker, 2017). Such surveys also reiterate the importance of ensuring that there is an earlier inclusion of FMs and clients as project stakeholders in the BIM process to ensure project success (Ashworth, Tucker & Druhman, 2019). The present paper addresses current BIM processes and the challenges faced by facilities management as project stakeholders in that process. To achieve this, success from a facilities management viewpoint is considered and barriers to facilities management success in BIM are explored.

1.1 Perspectives of Success

Success in construction project management is often judged by the 'Iron Triangle' of Time, Cost and Quality and has been used to measure the success of the PM process for decades (Atkinson, 1999). However, the 'Iron Triangle' does not consider the subsequent operational success of the project, merely management of the project delivery process (Ika, 2009). This distinction is expanded by Baccarini (1999) who splits success into two components, 'project management success' and 'end-product' success, which are independent of each other. De Wit (1988) upheld that projects can be over budget and behind time, but if the product met the quality requirements and achieved the operational requirements stipulated by the client, it could be considered a successful product, even if the management of the project had not been successful in meeting budget or time targets.

1.2 Facilities Managers as Project Stakeholders

Cooke-Davies (2002) attributes a projects long-term benefits to those involved in managing the operational phase of a building, namely the Facility Managers (FMs). FMs play a crucial role in delivering value and cost savings to the operational phase of the whole life cycle (WLC). It is estimated that 60% of operational costs of a building are attributed to the overall cost of an asset, and that 80% of these costs are influenced during the first 20% of the design process (ISO, 2017). Therefore, early inclusion of FMs expertise in construction is crucial to realising long-term cost saving and benefits of the built asset (Ackamete et al., 2010; Ashworth et al., 2016). However, there have been a number of inherent barriers associated with the integration of FMs as key stakeholders in the design and construction phase. These have included the aforementioned differences in what constitutes success, as well as poor engagement with FMs. In addition to these, there are other well documented issues such as: industry fragmentation and pervading silo mentalities (Miettinen & Paavola, 2014); inefficient collaboration; lack of communication between stakeholders (Azhar, 2011); adversarial contractual relationships; inefficient use of technology, and; poor understanding of operational requirements from other project members.

1.3 Challenges of the construction process for FMs

These barriers underpin one of the biggest challenges experienced at the operational and decommissioning stages of an asset, the flow of information. The construction process: "is highly reliant on the management, flow and usage of information… Much communication between the disciplines is normally necessary in such a process" (Tizani, 2007, p. 15). Several researchers discuss the problems in the current practice around loss of knowledge and information as a project progresses, from concept, through design, to construction, operation and finally decommissioning (Demian & Walters, 2013; Parsanezhad & Dimyadi, 2013; Yalcinkaya & Singh, 2014). Furthermore, the outputs that are delivered to FMs are usually delivered in hardcopy or e-paper as Operations and Maintenance Manuals (OMM), resulting in the information being voluminous to store, laborious to catalogue, difficult to search and slow to access (Patacas et al., 2015). This results in poor facility performance, much wasted time trying to capture, transfer and catalogue data from design and construction phases (Patacas et al., 2015, Kasprzak & Dubler, 2012). Another difficulty faced by project teams are the silo mentalities frequently experienced in practice (Miettinen & Paavola, 2014), where each part of the team works in relative isolation. This leads to individual work package optimisation rather than whole project optimization. Such difficulties are further compounded by inefficient communication (Azhar, 2011).

1.4 The Progress of BIM

Although BIM is no longer cutting-edge, it is still "seen by many as being a disruptive innovation, which is bringing about the reconfiguration of practices in the AEC industry" (Poirier et al., 2015, p. 46). BIM is more than technology change; it is a collaborative approach with the potential to be a paradigm shift in the AEC industry (Gerrard et al., 2010). The BIM process helps to manage the flow and usage of information by allowing the reuse of data, reducing the need for re-inputting of data by different specialists and reducing the chance for human error (Azhar, 2011). BIM also has potential for improving handover, as data can be exported from the model in a suitable format for FM purposes (Wu & Issa, 2012). Implicit in BIM is greater sharing of information, which enables a more collaborative working environment. In practical terms, this means using a common data environment (CDE), as a reliable single source of information (Volk et al., 2014). There is also potential for cost savings via the digital information generated during the construction process for FM purposes, with an estimate that two thirds of potential savings from BIM use would be by FMs and owners (Gallaher et al., 2004). FMs have a lot to gain from using BIM, but it is not being widely achieved. The FM Awareness of BIM (2017) report found that only 39.8% had some experience of being involved in a BIM project but only 20.5% (combined) have direct experience of writing or implementing an Asset Management Strategy in line with ISO 55000 or other system." (Ashworth & Tucker, 2017). The annual NBS BIM Surveys report increasing potential for BIM use in FM, with the number of projects producing COBie data increasing year by year, from 15% in 2012, to 23% in 2013, 27% in 2016 (NBS, 2016) and 41% in 2018 (NBS, 2018). However, in an alternative 2017 report, of 254 respondents, many noted that they were neutral with regards to the use of COBie for transfer into CAFM/other systems. It was indicated that the reason for this may be that FMs see COBie as just part of the process (Ashworth & Tucker, 2017) Many researchers have discussed this apparent lack of progress with BIM for FM, noting difficulties in defining which information is valuable for FMs and the lack of early engagement with FMs (Alwan & Gledson, 2015; Wijekoon et al., 2016).

1.5 BIM in the Operational Phase

BIM for FM is relatively new compared to the other phases of construction and, as such, there appears to be a lack of client demand. In order to get the relevant information into the model, FMs need to specify in their Asset Information Requirements (AIRs) what they want, however, "very few owners have defined these informational needs or developed an integration strategy into existing maintenance management systems" (Kasprzak & Dubler, 2012). It seems that the potential benefits of BIM to the operational phase of the building are being hampered by lack of knowledge by building owners and operators. Giel & Issa (2014, p.552) state that, “many owners are unsure of what BIM deliverables to require and lack the technical knowledge and resources required to operationalize the models they receive from designers and contractors”. The same researchers (ibid) advise, “there is a need to truly understand the information needs of FM professionals before requirements documentation are refined”, which is supported by Kasprzak & Dubler (2012, p. 68) in that, “very few owners have defined these informational needs or developed an integration strategy into existing maintenance management systems.” Other researchers point out that there are difficulties defining data requirements for FM (Yalcinkaya and Singh, 2014), and additionally prioritising which information is needed at what time during the project delivery (Kassem et al., 2015).

1.6 Conceptual Model

The concepts which have emerged from a review of the literature have been synthesized to construct a framework diagrammatically presenting the key issue and its possible causes by way of a Fishbone model (as popularized by Kaoru Ishikawa) shown in Figure 1. The ‘problem’ or key issue, is success in the operational phase of the project lifecycle, and the concepts identified in the literature are all possible causes that have an impact on operational success[1].

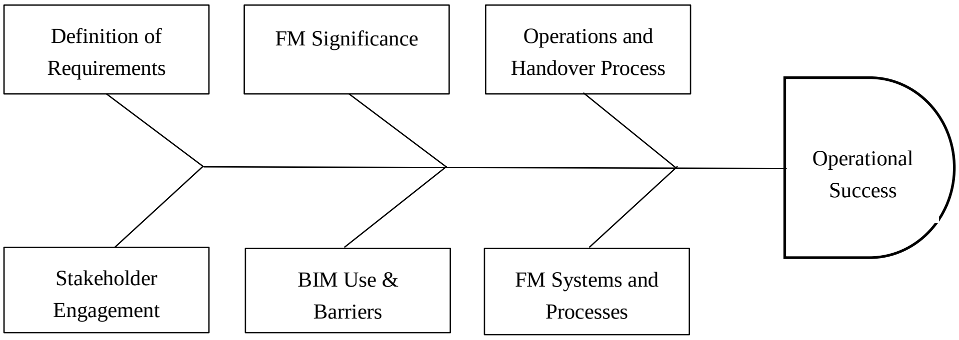


Figure 1: Theoretical model of the themes identified in the literature

2. Methodology

Qualitative research, informed by an interpretivist epistemology and an inductive approach was undertaken, using semi-structured interviews to collect data from a non-probability sample. The population of interest were project professionals from the project-, and facility-, management domains. Use of a convenience, purposive, sampling strategy afforded 7 interviews to be undertaken. These were with 4 FMs and 3 PMs, all of whom were currently engaged in construction projects and whose experience in the industry ranged from 6 – 40 years. They were drawn across five separate organisations based in the North of England, UK (see Table 1 for details of research particpants). The interview guide was distributed two weeks before each interview took place, along with a reminder letter, to enable the participants to prepare and as such generate more considered data. Use of semi-structured interviews also allowed for some question development to occur, whereby some unexpected themes that arose from the initial, early interviews could be incorporated into the research instrument. The interviews were recorded using a digital voice recorder and then transcribed. Anonymous participant numbering was also allocated to research participants. To aid thematic analysis of qualitative data, Nvivo was also used.

[1] As the research has been undertaken from a qualitative only perspective, the researchers have refrained from using terminology of independent and dependent variables here, despite how well Ishikawa models also lend themselves to quantitative analysis of cause and effect.

Table 1: Characteristics of Research Participants (RP).

RP	Role	Experience	Sector.	Organisation.
1	FM, Head of Maintenance.	40 years.	Higher Education.	1: Newcastle.
2	PM, Senior Programme Manager.	19 years.	Local Government.	2: Cumbria.
3	Project Manager.	7 years.	Higher Education.	1: Newcastle.
4	FM, Estates Planning & Development Manager.	23 years.	Higher Education	3: Sunderland.
5	FM, Senior Maintenance Supervisor.	14 years.	Higher Education.	4: Lancaster.
6	Project Manager.	6 years	Higher Education.	3: Sunderland.
7	Property and Facilities Manager.	5 years.	Heritage.	5. Durham.

3. Results and Analysis

a. Success

Prior research identifies that the 'Iron Triangle' is a commonly used method to analyse project success (Atkinson, 1999). Other researchers (Baccarini, 1999; Ika, 2009) report that PMs look at project success, while FMs are more concerned with end product success. Literature tends to identify that tight profit margins leads to adversarial approaches being taken, which along with a tendency to work in silos with poor communication can impact on success (Miettinen & Paavola, 2014). Because of these concerns, participants were asked: ***How do you judge if a project was successful?*** This question generated various responses focusing on issues such as success measurability, client and end-user satisfaction, and quality of collaborator relationships. Although not mentioned by name, many participants talked about the iron triangle, including Participant 6 (PM) who said: "*There are three key elements, time quality and cost, two are easy… quality is a lot harder.*" Operational success was mentioned by some respondents, such as Participant 1 (FM): "*Is it easy to maintain,* [and] *does it work is the fundamental one… if it doesn't work properly, it's hopeless.*" Customer satisfaction was raised as a measure of success by Participant 3 (PM): "*On time, on budget, but the main thing is if the client is satisfied.*" While Participant 7 (FM) said "*My customers are the people who work here, so as long as they get what they need… then that is the success of it.*" Several participants reported that adversarial relations were indeed common and impacted negatively on success, Participant 1 (FM) said, "*in value engineering the contractors will go to their preferred supplier and say this is what you are after, but it isn't, in reality, so we do spend a lot of time arguing with them about that.*" Silos were also mentioned as a barrier to success, even with in house PM / FM teams, Participant 6 (PM) said, "*because we maintain our own estate…we have a serious incentive to involve our FM guys. Unfortunately, that is not always very forthcoming.*"

b. Stakeholders

FMs were mentioned as important stakeholders due to the lifecycle costs of a building outweighing construction costs (Ashworth et al., 2016, Patacas et al., 2015). Participants were separately asked: (PMs) Where would you place FMs on a scale of stakeholder importance and why? / (FMs) At which points were you involved in the project delivery? PMs reported FMs as high importance, just below the end user. FMs felt that they were sufficiently engaged, but not sufficiently listened to. Participant 2 (PM) said: "I would put them up there with the likes of the project sponsor, because the FMs are going to be the ones who are operating the building and maintaining it." Lifecycle costs were important to PMs, with Participant 4 (PM) saying: "we get the money from capital for projects, but long term our revenue budgets aren't huge, so we need to make sure that we are specifying good long-term value for money." All FMs reported that they were engaged throughout the project, from early on in developing the brief, through to signing off changes due to value engineering, however their concerns were not always acted upon. Participant 1 (FM) said “once it gets through outline design and it goes to the contractors for detailed design, we are involved then and that is when the arguments start, because they want to give you something you don’t want, cos its cheap as chips for them.”

c. BIM for FM, use and barriers

Surveys of AEC professionals (Eadie et al., 2013, NBS, 2016-2018) report that BIM for FM is lagging behind BIM adoption for other purposes. Wu and Issa (2012) suggest that BIM has significant potential for FM, but it is not being realised. Participants were asked a series of questions on BIM: Do you currently use BIM, if so what for? What benefits can you see in using BIM for FM? What is stopping you from using BIM for FM? Interestingly, no participants reported currently using BIM for FM, with no one using a 3D model or asset information from a model for FM purposes, in contrast with widespread use of BIM in design, stakeholder engagement and construction. A key difficulty mentioned by several participants was that current FM software couldn’t readily import models or COBie data, despite software manufacturer claims. Participant 2 (PM) reported, “BIM is being used for design, coordination, clash detection, we are using a common data environment for the sharing documents, but not yet for FM.” Several respondents were unconvinced about the ability of BIM to meet their needs, or offer a significant improvement over their current systems. Participant 1 (FM) noted that, “I’m sceptical, because I haven’t found a software system yet that does anything near what people tell you it can do.” This was echoed by Participant 3 (PM) who said: “We have just purchased an add-on for our CAFM system to import BIM data, but it is not really able to import models and COBie data right now without a lot of fiddling and re-mapping of fields.” Lack of awareness of BIM was mentioned by several respondents, Participant 6 (PM) said “there was a significant amount of education we had to do with the FM team, even to bring them up to a basic awareness of what could be done with BIM… People are busy doing their day job, keeping up on new software advances is pretty far outside their usual role.” Several respondents pointed out that even if there was software available which could deliver, there is an element of resistance, with Participant 3 (PM) commenting “We need to make people aware within the FM crowd, because they are resistant to change, they are very traditional in the way they work.” This was echoed by Participant 7 (FM) who remarked “I think people are reluctant to change away from a system that works, even if it is not very efficient.” Other barriers such as the cost of implementing a new process and a lack of skilled staff were also reported by Participant 4 (FM), “the other thing is resource, you need someone to coordinate the process, we are struggling to deliver the projects as they are at the moment...the start-up costs are prohibitive.” This was supported by Participant 6 (PM) who said: “The complexity of changing CAFM systems and the amount of data we have makes adopting a new system quite laborious, very expensive really. Despite the potential savings it is really the upfront costs and finding the time, getting people with the right knowledge who can actually deliver the potential for us.”

d. Defining Requirements

Kasprzak & Dubler (2012) report that few owners have defined their FM requirements. This is supported by Giel & Issa (2014) who note that many owners are unsure what they require and that FMs need to be engaged to define these requirements. All Participants were asked a series of related questions: How are FM requirements for a building defined? At what point were FMs requirements discussed / mapped out? Have you developed Asset Information Requirements? Only two respondents (Participants 2 and 6) reported having comprehensive Asset Information Requirements (AIRs). Several others reported that they were developing AIRs, however everyone who had or was developing AIRs had brought in consultants to help develop their requirements, as they did not have the expertise in-house. However, some organisations had much less in the way of formal requirements and relied on looser specifications. Participant 2 (PM) reported: “we appointed a consultant to take us through that process and they drew up the Asset Information Requirements document.” Participant 6 (PM) described the process they went through to map out FM requirements, “we sat with the FM team and went through the COBie sheet, to see what information they needed, what they didn’t need, what they wanted embedded in the model, what could be linked to the model as a PDF, so we developed a full set of Asset

Information Requirements." Participant 4 (FM) commented: "We don't have a standard briefing document at the moment, that is probably what we need, but at the moment it is just using team members knowledge of historical successes and issues." Participant 7 (FM) described their process: "As part of going out to tender we write up our expectations, our requirements for O&M information and testing schedules." Participant 3 (PM) reported use of an internal design guide, which stated what type or brand of equipment to use or not use, but not what information was required to maintain it. "The briefing document is owned and updated by the FM team, it is their design bible for projects." Participant 4 (FM) noted that some asset information was requested however, "I don't think we go into that level of detail for the different assets."

e. Loss of information at handover

Many researchers note that loss of information at handover is a big problem for FM, which BIM could help to resolve (Demian & Walters, 2013, Patacas et al., 2015, Parsanezhad & Dimyadi, 2013). Participants were thus asked: Can you give me an overview of your processes for handover / receiving maintainable asset information? Do you use, or have you considered using BIM to assist with handover? Both PMs and FMs reported struggles with traditional handover practice, no participants reported using BIM data at handover. Participant 1 (FM) said "you get a pile of O&Ms with some brochures in." Some respondents reported having adopted soft landings procedures to assist with handover, such as Participant 3 (PM) who noted, "we have been operating BSRIA soft landings over the last few years." And Participant 6 (PM) who said, "we follow the FMAP42 process, which walks through all the different parts of handover." Participant 3 (PM) was keen to explore the possibilities of BIM at handover, but noted "I have not actually worked on a project using BIM which has got to that stage yet."

f. Operational Information

Studies by Gallaher et al., (2004) and Patacas et al., (2015) report challenges with O&Ms that BIM should help to solve. Participants were asked: How do you access O&Ms currently? Do you use / have you considered using BIM to assist with building operations and asset management? Participants were united in their agreement that current practices were inefficient, with either not enough information or not specific enough information being delivered. Reliance on paper and scanned documents was still widespread. None of the respondents had any success with importing COBie data into their CAFM system. Participant 5 (FM) noted: "The main problem we have is that most of the O&Ms we get are the full product catalogue, it can be difficult to get the exact information that we need out of that." Participant 1 (FM) remarked: "I could take you to a storage unit which is full of O&Ms." No-one reported successful use of a standard classification system. Participant 6 (PM) said "Our O&Ms are scanned in, we get them as hard copy or pdfs, they are put into our central database. We don't really have a standard format or naming system, which can cause issues for the maintenance guys trying to find the right information." Participant 3 (PM) reported "In terms of O&M format we have guidance notes that go out to the design team and contractors that defines exactly what needs to be where, the previous version was a bit woolly and we didn't get what we wanted." Several respondents reported struggling to import BIM data from the design and construction phase into their CAFM systems. Participant 1 (FM) noted that "the FM software providers all said, oh yeah we can do that, in reality none of them can."

4. Discussion

The data from this study broadly followed the split identified in the literature (Baccarini, 1999), with PMs more concerned about project management success and FMs giving more weight to end-product success. However, both groups reported that the best measure of success was a satisfied client or end user. The disconnect between project management success and long-term project success (Munns and Bjeirmi 1996) was raised by several respondents. Results also highlighted a disconnect between PMs assessment of stakeholder importance and how FMs felt they were treated. PMs regarded FMs with high importance as identified in the literature (Ashworth et al., 2016). However, FMs stated that their concerns were sometimes excluded due to the type of contract used, or cost implications. FMs reported being over-ridden by other demands such as meeting the project budget. Despite most of the respondents working for large public-sector organisations, there was a clear lack of BIM for FM use. A key finding, here, not widely reported in the literature, is that most FM software is still unable to readily import COBie data and 3D models in any format. However, there are now some interoperable CAFM solutions with upstream BIM workflows, meaning those identifying this as a barrier, could be demonstrating a lack of current knowledge. Despite this, and the fairly widespread uptake of BIM for design and construction, information is still nonetheless being lost at handover, or at least not being utilized by the building operators. Reluctance to change FM software was a major barrier, as is was perceived as a paradigm shift (Gerrard et. al, 2010) and a disruptive innovation (Gledson, 2016). Further reported barriers included; the cost associated with changing CAFM systems, the lack of knowledge within the FM sector of BIM capabilities and the additional cost to the project of requesting asset data in the BIM model. It was apparent from the results that there were some early adopters of BIM processes. However, there were some who were significantly further behind, reporting no standardised requirements document or no CAFM system, just a collection of spreadsheets. Most FMs reported being engaged to define requirements, but at varying levels of detail. This matches well with thoughts that most clients struggle to generate detailed requirements. The data shows that the defining of FM requirements for BIM is no longer an insurmountable barrier, but is still a significant challenge for FMs. The data collected shows no reported use of BIM for operational FM purposes, despite several respondents having completed projects which utilised BIM for design and construction and produced 3D as-built models and COBie data. This suggests that despite widespread BIM use at other project stages, information is still being lost at handover, as described by Patacas et al., (2015). Difficulty accessing operational information due to independent FM databases (Patacas et al., 2015) and, in some cases, continuing use of paper files and a lack of a standard classification or filing system was also reported. Overall FM's in this sample, were yet to be convinced about the ability of current FM software to utilise BIM data such as COBie sheets and 3D models for operational purposes and still provide the same capabilities as they have in existing FM software.

5. Conclusions, Limitations and Further Research

The aim of this study has been to understand what challenges FMs face in achieving successful outcomes using current construction project management practices and to ascertain if FMs do see BIM as a useful tool to help overcome these challenges. In the first instance there is a disconnect between the perception of success with FMs claiming that that the long-term product success of the built asset was overshadowed by the more traditional, short term project management success criteria of time, cost and quality. Despite the early engagement of FMs in the project process and the belief that FMs were seen as important stakeholders in the process by PMs, they felt that their concerns for the long-term success of the project were over ridden by demands such as meeting the project budget. Barriers to operational success identified that current FM processes were inefficient, particularly around handover with the loss of information at stage transition. In additions to this respondents also noted that adversarial relationships, silo working, working to poorly defined requirements and resistance to change were also barriers. The literature reported that BIM would enable huge efficiency savings and could revolutionise FM processes, however, A significant finding from the results found that BIM data, both 3D models and asset information was not readily compatible even with support from BIM consultants and specialist plugins for the latest FM software, they were still unable to import 3D models or COBie data into their CAFM systems. A comprehensive search of the literature brought up only one recent study highlighting that the primary barrier to adopting BIM for FM, suggesting that more research around the problem of software interoperability is needed. Whilst the findings are interesting, it must be stressed that the results from this study cannot be generalised due to the small sample size and the convenience sampling method used. However, the study has enabled the identification of several potential areas for future research: First, a quantitative survey using a probability sampling approach would help to ascertain if the findings of this study are representative of the wider FM population. Additionally, research into what barriers FMs face when developing Asset Information Requirements, as this was major challenge for many FMs and projects. Finally, a deeper technical study to gauge difficulties of interoperability between FM software and BIM outputs would benefit, as this was the primary barrier preventing FMs from utilising BIM data for operational purposes.

References

Alwan, Z. and Gledson, B.J. (2015). Towards green building performance evaluation using Asset Information Modelling. Built Environment Project and Asset Management, 5(3): 290–303.

Arayici, Y., Onyenobi, T. and Egbu, C. (2012). Building Information Modelling (BIM) for Facilities Management (FM): The MediaCity case study approach. International Journal of 3D Information Modelling, 1(1): 55-73.

Ashworth, S. and Tucker, M. (2017). FM awareness of Building Information Modelling (BIM): August 2017.

Ashworth, S., Tucker, M. and Druhmann, C.K. (2019). Critical success factors for facility management employer's information requirements (EIR) for BIM. Facilities, 37(1/2): 103-118.

Ashworth, S., Tucker, M., Druhmann, C. and Kassem, M. (2016). Integration of FM expertise and end user needs in the BIM process using the Employer's Information Requirements (EIR). Proceedings of CIB World Building Congress.

Atkinson, R. (1999). Project management: cost, time and quality, two best guesses and a phenomenon, it's time to accept other success criteria. International journal of project management, 17(6): 337-342.

Azhar, S. (2011). Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. Leadership and Management in Engineering, 11(3): 241-252.

Baccarini, D. (1999). The logical framework method for defining project success. Project management journal, 30(4): 25-32.

Cooke-Davies, T. (2002). The real success factors on projects. International Journal of Project Management, 20(3): 185–190.

Demian, P. and Walters, D. (2013). The advantages of information management through building information modelling. Construction Management and Economics, 32(12): 1153-1165.

de Wit, A. (1988). Measurement of project success. International Journal of Project Management, 6(3): 164–170.

Eadie, R., Browne, M., Odeyinka, H., McKeown, C. and McNiff, S. (2013). BIM implementation throughout the UK construction project lifecycle: An analysis. Automation in Construction, 36: 145-151.

Gallaher, M. P., O'Connor, A. C., Dettbarn, J. L., Jr. and Gilday, L. T. (2004). Cost analysis of inadequate interoperability in the US capital facilities industry: National Institute of Standards and Technology (NIST).

Gerrard, A., Zuo, J., Zillante, G. and Skitmore, M. (2010). Building information modeling in the Australian architecture engineering and construction industry: Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies: IGI Global, 521-545.

Giel, B. and Issa, R. R. (2014). Framework for evaluating the BIM competencies of facility owners. Computing in Civil and Building Engineering. 552-559.

Gledson, B. J. (2016). Hybrid project delivery processes observed in constructor BIM innovation adoption. Construction Innovation, 16(2): 229-246.

HM Government (2011, 2016) Government Construction Strategies: HM Government. Both available at: https://www.gov.uk/government/publications/government-construction-strategy-2016-2020

Ika, L. A. (2009). Project success as a topic in project management journals. Project Management Journal, 40(4): 6-19.

Kasprzak, C. and Dubler, C. (2012). Aligning BIM with FM: streamlining the process for future projects. Construction Economics and Building, 12(4): 68-77.

Kassem, M., Kelly, G., Dawood, N., Serginson, M. and Lockley, S. (2015) BIM in facilities management applications: a case study of a large university complex. Built Environment Project and Asset Management, 5(3): 261-277.

Korpela, J., Miettinen, R., Salmikivi, T. and Ihalainen, J. (2015). The challenges and potentials of utilizing building information modelling in facility management: the case of the Center for Properties and Facilities of the University of Helsinki. Construction Management and Economics, 33(1): 3-17.

Miettinen, R. and Paavola, S. (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. Automation in Construction, 43:84-91.

Munns, A. K. and Bjeirmi, B. F. (1996). The role of project management in achieving project success. International Journal of Project Management, 14(2): 81-87.

NBS (2016, 2017, 2018) National BIM Reports, Newcastle, The NBS.

Parsanezhad, P. and Dimyadi, J. (2013). Effective facility management and operations via a BIM-based integrated information system.

Patacas, J., Dawood, N., Vukovic, V. and Kassem, M. (2015). BIM for facilities management: evaluating BIM standards in asset register creation and service life. Journal of Information Technology in Construction (ITcon), 20(20): 313-331.

Poirier, E., Staub-French, S. and Forgues, D. (2015). Embedded contexts of innovation. Construction Innovation, 15(1): 42-65.

Sabol, L. (2008) Building Information Modeling & Facility Management. New York: Taylor & Francis.

Tizani, W. (2007) 'Engineering Design', in Aound, G., Lee, A. and Wu, S. (ed.) Constructing the future: nD modelling. New York: Taylor & Francis, 14-39.

Volk, R., Stengel, J. and Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. Automation in Construction, 38:109-127.

Wu, W. and Issa, R. (2012). BIM-Enabled Building Commissioning and Handover. International Conference on Computing in Civil Engineering, Clearwater Beach, Florida, United States: American Society of Civil Engineers, 234-244.

Yalcinkaya, M. and Singh, V. (2014). Building Information Modeling (BIM) for Facilities Management–literature review and future needs. IFIP International Conference on Product Lifecycle Management: Springer, 1-10.

Analysis of Airport BIM Implementation through Multi-Party Perspectives in Construction Technology Ecosystem: A Construction Innovation Framework Approach

Basak Keskin[1*], Baris Salman[2], Beliz Ozorhon[3]
[1,2] Syracuse University
[3] Bogazici University
* email: bkeskin@syr.edu

Abstract

Airports encompass highly complex and fragmented building and business systems that inaugurate high value interactions between people, places, and things. Value creation is a recurring issue in airport projects. Accordingly, as a highly important economic engine, life cycle management of airport projects through design-build-operate stages requires innovative approaches to meet ever-evolving needs of end-users. Building Information Modeling (BIM) can be considered as a key process innovation that can tackle the aforementioned issues while enhancing connectivity between different construction technology solutions. In this study, a construction innovation framework is employed to analyze airport BIM implementation processes of different parties, including the client, general contractor, consultant, and technology vendor. This framework enables the analysis of BIM implementation process based on various components such as drivers, inputs, enablers, barriers, benefits, and impacts. Multi-party perspective approach is adopted to explore these components for a large size U.S. airport project. It is found that the primary driver for BIM implementation is fast realization of quantifiable value- such as fewer safety issues provided by less rework on site- by the Owner. Major enablers are perceived as simplifying BIM processes and BIM tools interfaces according to project individuals' competencies and realizing potential synergies between different platforms and construction management processes; whereas rapid change of BIM tools and platforms, and significant resistance of upstream project personnel are regarded as major barriers. Based on the findings, determining BIM requirements and scope while avoiding ambiguity for each party enables continuous value creation throughout BIM implementation processes in an airport project. This study helps in understanding how BIM diffuses within an airport project context by articulating the dynamic relationships between key people, technology, and processes.

Keywords: Airport building information modeling (BIM) implementation, Construction innovation, Construction technology landscape, Connectivity, Multi-party collaboration

1. Introduction

In today's developing world, aging infrastructure falls short of addressing the hyper-evolving demands of the society. Modernizing and expanding infrastructure becomes increasingly important. Annual infrastructure investment needs for transport (road, rail, ports, and airports) continues to rise through 2030 to keep up with projected GDP growth; and it is estimated that an additional annual $2.5 trillion is needed in infrastructure investment through 2030 (MGI, 2013). Airports -forming one of the most important economic engines- play a crucial role within the infrastructure and urban development industry as hosting high value interactions between people, places, and things. They encapsulate various types of infrastructure, building and business systems. However, Airports Council International (ACI) World Key Performance Indicators (KPIs) (2019) reports that two-thirds of world airports are loss-making (Airports Council International (ACI) World, 2019). To increase infrastructure productivity, the delivery of projects -starting from the selection to building, and operation- should be streamlined by proven innovative practices (MGI, 2013).

Building Information Modeling (BIM) is increasingly employed as one of the most promising digital, innovative processes for transportation infrastructure projects, providing a more efficient management of network of assets in terms of scope, cost, time, quality, and resources from construction to operation (Bradley, Li, Lark, & Dunn, 2016; Costin, Adibfar, Hu, & Chen, 2018; Fortin, Bloomfield, Mahaz, & Alfaqih, 2018). According to Smart Market Report by Dodge Data & Analytics, the adoption levels of BIM use in transportation infrastructure is increasing; and 62% of the firms doing aviation projects have a higher level of BIM implementation in the majority of their projects compared to the ones having roads, bridges, rail/mass transit or tunnel projects in their portfolios. It is also reported that BIM use has been more than doubled in the US, UK, France, and Germany since 2015; and there is as a consistent trend that the designers are early adopters, and contractors are experiencing comparatively higher rate in BIM implementation despite having owner requests for BIM for roughly 35% of their projects (Petrullo et al., 2017). Increasing adoption of BIM implementation by firms with different roles focusing on aviation projects also implies the introduction of various other technology ecosystem use cases along with BIM to the airport projects. These use cases can be incorporated with the BIM implementation processes within the relevant project phases. The essential ones in which BIM technologies and processes create synergies in airport projects can be listed as 3-D modeling, lean construction, process simulation, value engineering, document management, project scheduling, design simulation (Koseoglu & Nurtan-Gunes, 2018; McCuen & Pittenger, 2016).

Moreover, connectivity between the aforementioned construction technologies and along the project supply chain network is crucial as it requires a certain level of collaboration between project parties. Because every party brings its own practices, sustaining a certain level of information flow throughout the supply chain network of the project is critical. In essence, it is important for every project participant to understand that the collaborative process within the BIM-enabled project leads to higher efficiency (Lu, Zhang, & Rowlinson, 2013). This notion becomes more complicated for airport projects as they typically have large scopes, long time periods between planning to completion; and they involve a wide variety of stakeholders (Sentence, 2013). Efficient deployment of airport BIM implementation can target challenges associated with seamless data handover between project parties and phases that occur due to siloed nature of airport projects. However, it is essential to understand the interactions both within a range of stakeholders, and between stakeholders and technology uses (Harty, 2005). Accordingly, the major objective of this study is to provide a solid understanding in how airport BIM processes can facilitate the delivery of a project by delineating the multi-party perspectives within a construction technology ecosystem.

1.1. BIM as an Innovation Process in Construction

BIM was an accepted acronym for a range of descriptions such as Virtual Design & Construction (VDC), integrated Project Models, or Building Product Models, but its single use and definition were standardized for Architecture, Engineering, and Construction (AEC) industry to holistically address planning, design, delivery, and operational processes within the building lifecycle (Dominik Holzer, 2016). Since then, BIM has been widely recognized as one of the disruptive digital innovations in the AEC sector. To explore BIM adoption's evolvement and diffusion as a construction innovation at the firm level and project level, several models, frameworks, and approaches have been suggested in the literature. It is discussed that considering the inter-organizational contexts of construction industry, BIM is an innovation that extends beyond a confined circle of application and has an inter-organizational level of effect in a project (Harty, 2005; Riitta & Hirvensalo, 2008; Shibeika & Harty, 2015). However, most of the literature has investigated construction innovation processes at the firm level, and the project level studies generally focus solely on building project case studies to analyze BIM implementation processes, lacking clear differentiation of multi-party perspectives.

BIM use facilitates the delivery of a project by enhancing the connectivity between parties and construction technology ecosystem use cases. In this study, interacting components of an innovation framework developed by Ozorhon (2013) are utilized to systematically analyze BIM implementation technology and processes from an innovation diffusion process approach in a complex large-scale project setting. The adopted framework is demonstrated in Figure 1.

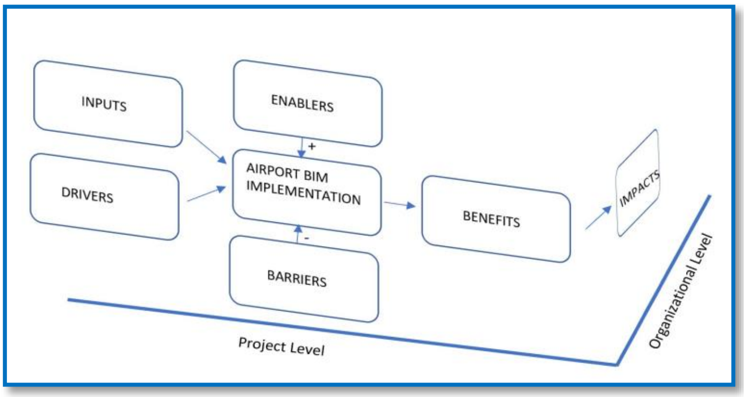


Figure 1: Framework for the Innovation Process of Airport BIM Implementation (adopted from (Ozorhon, 2013)*)*

In this framework, drivers represent main motivations for BIM implementation, and inputs represent resources utilized during the implementation process. The rate of innovation is influenced by barriers and enablers. Barriers are the primary factors that hinder BIM implementation. Enablers act as the factors that are used to overcome the barriers. The outcomes of the BIM implementation are represented by benefits which are realized at the project level. Wider outcomes are defined by impacts that are observed at the organizational or firm level in the long run. According to this framework, it is assumed that project-level benefits trigger the impacts realized at the organizational level. These components are examined in a complex large-scale airport case study to depict a clear picture of how Airport BIM implementation diffuses within a project environment from multi-party perspectives.

2. Material and Methods

This research uses a qualitative methodology, in which an explanatory case-study approach is followed via semi-structured interviews for data collection. Explanatory case studies focus on specific cases in which the theory, and its potential can be examined with the logic of replication to produce generalizations (Scapens, 1990). Also, to make conceptual generalizations from the local context of the case study to other settings, systematic collection of data from interviews, observation and documentation reviews are carried out (Seale, 1999). In this study, the fifth busiest U.S. large hub (a commercial airport classification having a minimum number of annual passenger boardings of 1 million (FAA, 2018)), Denver International Airport (DEN), is used as a case study. DEN is the largest airport in the US with 6 runways, spanning 136 km^2, and handling 61.4 million passengers annually (Dugdale, 2018). Also, DEN has been selected as the best among the 20 largest U.S. airports according to the first WSJ Airport Rankings (McCartney, 2018). The case study investigates BIM-enabled project delivery and life cycle management of DEN via focusing on DEN’s completed expansion project of Hotel and Transit Center Program, containing a commuter rail transit center and a 519-room hotel, and current digital facilities and asset management practices. This case is chosen strategically to address the problem statement and to provide an in-depth analysis by answering questions of “how” and “why” (Yin, 1994) from multi-party perspectives. With an understanding of the existence of different stakeholders and different perspectives, semi-structured interviews are carried out with four different parties representing the Owner, General Contractor, Supplier (technology/software vendor), and Consultant as the owner’s representative. The roles of the interviewees are provided in detail in Table 1. Each participant oversees the airport BIM implementation process within their respective organizations. As such, yielded data encompass insights on upstream to downstream activities within organizations. Semi-structured interview questions are provided in Table 2.

Furthermore, thematic analysis is used to identify patterns and themes in the qualitative data collected. Thematic analysis begins at the stage of data collection, data entry and continues throughout data coding and interpretation (Evans & Lewis, 2017). In this study, themes are determined as the components of an innovation framework, which are drivers, inputs, enablers, barriers, benefits, and impacts. The qualitative data collected via each interview question is coded with the associated themes (See Table 2). A qualitative data analysis computer software package, NVivo, is used to code the collected data to provide an in-depth case analysis by developing links between the themes and the original data coming from interviewees' answers. Themes are represented as nodes in the NVivo interface and interviewee's responses are imported as cases to the NVivo project. The coding patterns are analyzed for each case by calculating the coding percentages for each theme.

Table 1: Interviewees' Roles and Organizations

Interviewee	Role	Organization
Digital Facilities and Infrastructure (DFI) Program Manager	- Building up the DFI Program including BIM, VDC and integrations with GIS and Asset Management - Implementing the rollout of a bidirectional connection between airport BIM models and the airport asset management program - Developing workflows that improved the warranty management program by integrating it with other newly deployed platforms to create additional synergies	Owner
Senior Integrated Construction Manager	- Manage projects/teams from pre-construction through occupancy by utilizing VDC - Implementing training programs on VDC uses - Leading the integrated delivery process in pre-construction - Assisting in creation of company-wide VDC standards, and streamlining the BIM execution plan - Benchmarking emerging technologies including laser scanning	General Contractor
Principal Sales Consultant	- Offering insights and hands-on experience of innovative construction technologies - Providing pre-sales activity up to the executive level, consulting and professional services with Software as a Service (SaaS) platform, and connected BIM	Supplier (Technology Vendor)
Global Aviation Business Line Senior BIM Program Manager	- Working with owners, designers, and contractors in developing BIM processes for airport owners under all types of project delivery methods - Guiding clients in setting expectations and integrating BIM processes for comprehensive program development for integrated maintenance and management activities	Consultant

Table 2: Interview Questions with Coded Themes

Interview Questions	Theme
How do you customize an Airport BIM implementation strategy for your airport project?	Drivers, Inputs, Enablers
Could you describe how your BIM strategy addresses potential needs of the major project parties?	Drivers, Enablers
Could you describe the bottlenecks in BIM data flow between parties and/or phases of the project?	Barriers
Could you tell us your expectations for Airport BIM implementation outcomes in this project?	Benefits, Impacts
What are the current demands in BIM implementation processes considering current state of the art in the infrastructure sector?	Barriers, Drivers, Enablers
Could you tell us how you utilize BIM data?	Enablers, Benefits, Impacts

3. Results

The qualitative data collected through semi-structured interviews is systematically analyzed according to the data protocol (themes) demonstrated in Table 2 in the previous section. The coding summary, presenting the percentage of coding provided for each theme (component) by each party, is given in Figure 2.

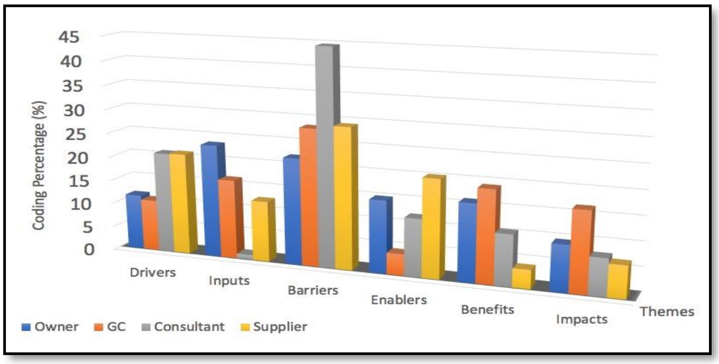


Figure 2: Coding Percentages of Themes from Multi-Party Perspectives

It is seen that 'Barriers' is the most coded component, and the rich-feedback for the barriers in airport BIM implementation shows that parties need to focus on enhancing their enablers or providing new enablers to support innovation in their projects. The Consultant has the highest coding percentage for barriers, and it is aligned with his responsibility requiring high awareness of potential challenges on the long-run to strategize optimum BIM implementation for such a large-scale project. On the other hand, the Consultant has the least input for 'Inputs' while the Owner has the highest coding percentage. This is because the Consultant sees the "big picture", but the Owner both finances and uses the BIM resources hands-on. Thus, the Consultant gives more insights on 'Drivers' as he triggers and observes BIM implementation process for different projects. However, for 'Enablers', it is the Supplier who has the highest coding percentage. Because the enablers are mainly represented by extended use of BIM technologies for better data management and utilization, the Supplier could give richer insights. Besides, more homogeneous distribution of the percentage coverage of the coding for the Owner indicates his centrality in the ecosystem as having similar levels of experience in each component. Furthermore, the Supplier has the least coverage for 'Benefits' as his project-level observation is more limited than the other parties. On the other hand, the GC realizes the benefits and impacts significantly. This highlights the higher level of BIM implementation in the design & engineering and construction phases compared to the operations and maintenance in airport projects, and also, how the GC leverages the BIM experience in the organizational level by transferring the generated knowledge to other projects.

Further analysis on each component is provided in the following sections.

3.1 Drivers

Drivers represent the main motivations for airport BIM implementation. Given the case study features, a large-scale airport project delivery requires an innovative, and more digital approach centralizing the Owner requirements (Keskin, Ozorhon, & Koseoglu, 2018). There are also common factors that drive every party to contribute to the BIM processes. Safety, eliminating cost over-runs, reducing waste, reducing time, increasing quality, effective interface management, easy management and access to the project documentation, facilitated communication and decision making, government mandates, Owner/client requirements are major drivers for parties throughout the life cycle of the project. These common drivers can also be applicable to various type of projects.

However, in the case study, from the Owner's perspective, the most prominent driver is having a record model on cloud to have certain bidirectional connectivity of the airport BIM model and the airport's asset management program for sustaining operational efficiency of the airport. This driver is also significantly emphasized by the Consultant, as it was stated that saving time via leveraging the common data environment in the operations phase, which corresponds to the 70%-90% of the total ownership cost (TOC), is more important. As the Owner side sees the value of BIM use by fast quantification achieved by the pilot projects in the construction phase, the Owner directs and obliges other parties towards BIM delivery guided by the Owner's BIM execution plan, standards, and matrices. Thus, Owner's engagement becomes one of the key drivers for other parties. Accordingly, General Contractor (GC) reported having a record model with a total of 50000 assets on cloud leading to enhanced connectivity with concurrent engineering & design and construction as a driver. Continuous realizations of value by the Owner and GC representatives increase the demand for use of BIM tools and processes. Furthermore, Owner's support also provides an optimum environment for the Supplier to set up the tools and consult the project parties for better use and integration of the tools. As such, the Supplier is driven to push the Owner to a more digitized project environment by offering integration of IoT and smart sensors to track real-time project efficiency with detection of use times of the tools, and enhanced safety on site.

It can be stated that Owner's dedicated BIM team and centralizing Owner's operational requirements are the major drivers that motivate all parties.

3.2 Inputs

Inputs are the resources utilized during the airport BIM implementation process. BIM processes can be described as the utilization of BIM tools, which are categorized as either authoring or analysis tools, and approaches to improve project phases of planning, design, construction, facility management and operations (McCuen & Pittenger, 2016). Not only BIM tools, but also other resources such as emerging technologies that can potentially be integrated with the BIM processes can be considered as inputs. BIM software, database technologies, geographic information system (GIS), complimentary technologies belong to the technology field of the BIM activity (Succar, 2009). The use of technology field is guided by the standards, execution plans, and strategies used in the project.

The Supplier, as the technology/software vendor, gave clear insights on the current state-of-practice in terms of the BIM tools used and how they sustain the information flow between parties. As the variety of BIM tools increases, platform solutions are mostly preferred by the Owners. Informative dashboards showing the number of assigned issues, clashes, documents are useful to track performance throughout the upstream to downstream activities. Not only BIM tools, but also IoT and smart sensor technologies were suggested by the Supplier as a next step in utilizing platform solutions. The Owner side, as managing and controlling the BIM delivery, reported various BIM tools including Revit, AutoCAD Civil 3D, Navisworks, BIM 360, Esri ArcGIS, Bluebeam, and IBM Maximo that correspond to the whole project life cycle. The Owner provided BIM design standards including Revit families, project coordinates, shared global coordinates, scripts to automate the BIM processes, and digital facilities and infrastructure matrix showing the required design model level of detail (LOD) at each package deliverable (LOD 100 to LOD 300). The Owner also has a strategy of mobile BIM including an inspection team of 62 inspectors and 220 mobile tablets on site for quality assurance and quality control (QA/QC) purposes. To avoid interoperability and other data exchange problems, GC also uses same authoring tools, but additionally GC tracks performance on site by using Synchro, Oracle Aconex, and Point Layout. Furthermore, the Consultant provides the BIM strategy, which is optimized according to the project resources and scale, overseeing all parties' BIM delivery responsibilities. As a common ground, it was reported that Internet of Things (IoT) and smart sensor technology can facilitate risk management by providing a more effective control on site.

Overall, each party brings in various tools and approaches to the project ecosystem to execute their own BIM scope. However, these tools and approaches should be complimentary and supportive to execute a single integrated digital platform for the project.

3.3 Barriers

Barriers are the primary factors that hinder airport BIM implementation. Lack of financial resources, lack of clear benefits, unsupportive organizational culture, lack of experienced BIM professionals, lack of awareness, lack of governmental support, and level of project complexity can be listed as major barriers of BIM implementation (Keskin et.al., 2018). These barriers can evolve overtime and can show discrepancies among different project phases and different parties. Thus, BIM adopters should determine and prioritize the most vital ones for their project considering their BIM scope at the time.

In this case study, barriers reported are mostly related to the BIM data handover and cultural barriers. Due to the collaborative nature of BIM, one party's incompetency in BIM affects other parties' practices significantly. Accordingly, lack of alignment and/or integration of complimentary practices such as GIS and BIM are some of the major challenges for the Owner. Lack of technology readiness and lack of software vendor support and/or involvement are common barriers for BIM data-handover reported by the Owner and GC. According to the Supplier, the major challenge is the siloed nature of airport projects, featuring 15 different data silos on average. Converging data spaces of each party, and highly expanded communication networks requiring approval of project documents by different parties block seamless data handover. The Supplier also stated that budget constraints and lack of technology readiness mainly hinder the BIM implementation process. These factors also hinder the involvement of the Supplier according to the Owner and GC.

Furthermore, the limited number of resources in terms of team members and BIM tools is another barrier reported by both the Consultant and the Owner. Lack of support from the governing bodies at the state and municipal levels restricts the resources for the digital facilities team to pursue competitive BIM applications such as BIM-enabled facility management (FM). A budget-based approach for asset management is preferred instead of an asset-based approach. As another common point reported by the Owner and the Consultant, the scale and complexity of the airport project, which led to a significantly large asset pool, is challenging the BIM implementation in the facility management phase. According to the Consultant, barriers for advancing BIM implementation experiences in an airport context are also more prominent because of the ever-changing retail and airline concourses. This situation makes the required updates in the BIM model significantly more challenging in the FM phase.

Even for a well strategized BIM implementation plan for design & engineering and construction phases, pushing data to FM phase is still not seamless, and requires a gap analysis considering the operational specifics of the airport.

3.4. Enablers

Enablers act as factors that are used to overcome the barriers. The key constructs of enablers of BIM implementation can be given as strategic initiatives, change management, cultural readiness, learning orientation, knowledge capability, organizational structure, and process management (Abbasnejad, Nepal, & Drogemuller, 2016). Methods and strategies developed to overcome barriers also show certain variation among different parties due to the power of authority and resources they possess.

Taking strategic initiatives to generate key control mechanisms and incentives is a key enabler for the Owner. According to the Owner, BIM is not 'visible' to all parties such as technicians on site because the main idea is to facilitate the project delivery by BIM, where applicable. If BIM use confuses parties by disrupting their work efficiencies, there is no value in enforcing BIM. Thus, BIM is not introduced to certain downstream parties who would have significantly steep BIM learning curves with no realizable contribution to their scope of work. Similarly, for parties that need to implement BIM, aligning their BIM learning curves is a major enabler for the Owner. Centralizing BIM management on behalf of the Owner is another enabler that enhances all parties' speed in BIM delivery, and asset management capabilities of the airport in the FM phase. Additionally, as the Owner manages all BIM processes, optimizing time spent on improving integration and exploring new technology is also a crucial enabler for the Owner. The Consultant's key strategy that acts as an enabler is dissolving the boundaries between project phases by implementing an integrated project delivery mindset. A similar strategy is also grasped by the Supplier as he reported that the design of BIM platforms that provide clear deadlines for every issue visible to all upstream and downstream parties is a key enabler. The Supplier also perceives real-time continuous monitoring on site as another enabler, which can mostly provide benefits to the Owner.

Moreover, both the Owner and the General Contractor perceive certain application programming interfaces (APIs) as enablers for their airport BIM implementation processes. APIs enabling real time notifications for changes in projects, files, and folders, and interacting with 3D models in a web browser with no additional software needed are considered as enablers that can defer the problems with heavy airport models and expanded, siloed communication networks within the project. They can also be beneficial throughout the whole project life cycle.

3.5 Benefits

Benefits represent BIM implementation outcomes realized at the project level. BIM benefits can be presented as the way it creates synergies between other construction technology ecosystems' uses by providing an optimum base platform to utilize metadata for various project management purposes. Multidimensional capacity of BIM in performing project management practices brings clear benefits, such as organizing project schedule and budget, better coordination with the design team, optimizing the Owner's experience and satisfaction, increased profit margin, better control of the subcontractors, project closeout with facility information rich models (Bryde, Broquetas, & Volm, 2013).

Similarly, in the case study, utilizing BIM data efficiently for key project management practices within construction technology ecosystem for different phases of the project to extract actionable insights is the common benefit for all parties. The benefit of increased connectivity between project resources is expressed as direct relation between 3D modeling, design management, document management, quality control, and enterprise geospatial information services (eGIS) by both the Owner and the GC. On top of the listed construction technology uses, GC also benefits from BIM in project scheduling, quality control, progress tracking via performance dashboards, as-built model generation, cost control and concurrent engineering & design. The Consultant, Supplier, and Owner were more focused on the enhanced operational capacity by hosting a record model, which can guide the operator in asset management practices. The Supplier paid attention to how virtually navigating the airport model can increase wayfinding efficiency for end-users. Besides, because the Consultant oversees and guides the Owner for better customization of their BIM strategy, the Consultant is also mostly concerned with translating the BIM practices into faster delivery of the project with coordinated project timelines to make such a busy airport sustain its operational capacity for its passengers.

3.6. Impacts

Impacts are wider outcomes which are observed at the organizational or firm level in the long term. Knowledge gained as project-level benefits can be reusable and transferrable to create impacts at the organizational level. Organizations can experience improvements by benefiting from such impacts.

Airports are both building and business systems, and the impacts discussed by the multi-party perspectives focus mostly on business outcomes enhanced by airport BIM implementation for the whole project life cycle. As a common sense, to realize impacts in such a complex operational ecosystem, BIM should be implemented continuously by the support of all parties. According to the Consultant, developing a competitive edge for the airport is one of the key impacts because airports are not just competing for more passengers and being airline hubs, but also for reputation, which is highly linked to the best technology implementation. In a more detailed sense, according to the GC and the Owner, transferring the digital platform to the operations phase leads to positive impacts due to improvements in airport operations metrics, such as special airport systems service time, security checkpoints wait time, and baggage delivery wait time. All of these metrics affect the business performance of an airport. The Supplier highlighted that the collaboration power can be projected to the producer – customer – consumer chain by the knowledge generated during project delivery.

4. Conclusion

The competitive landscape of the infrastructure and urban development sector requires more innovative and digitally transformative solutions that unleash significant opportunities by connecting people, technology, and space starting from the very beginning of the project. As construction technology solutions become more connected, interactions of project stakeholders also increase along the supply chain network. These interactions and their influence are more prominent in large-scale complex project settings like airports. This study contributes to the body of knowledge and practice by presenting a high level and scalable novel approach to analyze BIM implementation for airport projects from multi-party perspectives through a real-life case study. This paper also provides a systematic understanding for how each party can have an impact on the level of BIM implementation diffusion by their own perspectives in a complex airport project.

Based on the research findings, the major barrier to airport BIM implementation is the highly-siloed airport systems coupled with existence of a technology-averse team, hindering the data handover processes. The major enabler is more transparent BIM platforms used with an integrated project delivery mindset. It is also seen that the perceived impacts of successful BIM implementation for an airport project are of concern to a significant number of parties as they hold significant business value. Accordingly, it can be recommended for all project parties to have BIM implementation roadmaps defining the expected business outcomes. In addition, all factors (from multi-party perspectives) determined for each component in the innovation framework should be assessed together as they are highly interdependent. Not only data transfer, but also data utilization, by connecting the project resources and project management practices in a construction ecosystem, is crucial for leveraging airport BIM implementation for a successful project delivery.

It should be noted that the findings presented in this study are reflecting conditions observed in a specific project. Caution should be exercised while extrapolating these findings to other projects. Further studies might consider the analysis of other airport projects, as well as other types of construction projects to enable comparison of BIM implementation process in different settings. Besides, additional projects may be analyzed in different countries and comparative studies may be produced to observe the similarities and differences regarding the country-specific factors.

Acknowledgements

The authors would like to acknowledge the support provided by Mr. Brendan Dillon. The authors would also like to thank the interviewees for their time and input.

References

Abbasnejad, B., Nepal, M., & Drogemuller, R. (2016). Key Enablers for Effective Management of BIM Implementation in Construction Firms. *Proceedings of the CIB World Building Congress 2016 - Creating Built Environments of New Opportunities*, *1*(June), 622–634.

Airports Council International (ACI) World. (2019). Airport KPIs reveal industry financial performance amidst capacity challenges - ACI World. Retrieved April 20, 2019, from https://aci.aero/news/2019/03/14/airport-kpis-reveal-industry-financial-performance-amidst-capacity-challenges/

Bradley, A., Li, H., Lark, R., & Dunn, S. (2016). BIM for infrastructure: An overall review and constructor perspective. *Automation in Construction*, *71*, 139–152. https://doi.org/10.1016/j.autcon.2016.08.019

Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of Building Information Modelling (BIM). *International Journal of Project Management*, *31*(7), 971–980. https://doi.org/10.1016/J.IJPROMAN.2012.12.001

Costin, A., Adibfar, A., Hu, H., & Chen, S. S. (2018). Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations. *Automation in Construction*, *94*(July), 257–281. https://doi.org/10.1016/j.autcon.2018.07.001

Dominik Holzer. (2016). The BIM Manager’s Handbook: Guidance for professionals in architecture, engineering, and construction. In *Statewide Agricultural Land Use Baseline 2015* (1 edition, Vol. 1). Wiley.

Dugdale, M. (2018). Airport Technology - The ten largest airports in America. Retrieved May 5, 2019, from https://www.airport-technology.com/features/largest-airports-america/

Evans, C., & Lewis, J. (2017). Analysing Semi-Structured Interviews Using Thematic Analysis: Exploring Voluntary Civic Participation Among Adults. In *Analysing Semi-Structured Interviews Using Thematic Analysis: Exploring Voluntary Civic Participation Among Adults*. https://doi.org/10.4135/9781526439284

FAA. (2018). Airport Categories. Retrieved April 22, 2019, from https://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/categories/

Fortin, J., Bloomfield, P., Mahaz, J., & Alfaqih, L. (2018). *Guidebook for Advanced Computerized Maintenance Management System Integration at Airports* (1st ed.; S. Lamberton, Ed.). https://doi.org/10.17226/25053

Harty, C. (2005). Innovation in construction: A sociology of technology approach. *Building Research and Information*, *33*(6), 512–522. https://doi.org/10.1080/09613210500288605

Keskin, B., Ozorhon, B., & Koseoglu, O. (2018). BIM Implementation in Mega Projects: Challenges and Enablers in the Istanbul Grand Airport (IGA) Project. In *Advances in Informatics and Computing in Civil and Construction Engineering* (pp. 881–888). https://doi.org/10.1007/978-3-030-00220-6_106

Koseoglu, O., & Nurtan-Gunes, E. T. (2018). Mobile BIM implementation and lean interaction on construction site: A case study of a complex airport project. *Engineering, Construction and Architectural Management*, *25*(10), 1298–1321. https://doi.org/10.1108/ECAM-08-2017-0188

Lu, W., Zhang, D., & Rowlinson, S. (2013). Bim Collaboration: a Conceptual Model and Its Characteristics. *29th Annual ARCOM Conference*, (September), 25–34. Retrieved from https://pdfs.semanticscholar.org/5c4a/9231833ab123a25ca3a79d232cde14899b4f.pdf

McCartney, S. (2018). The Best of the Biggest U.S. Airports - WSJ. Retrieved May 6, 2019, from https://www.wsj.com/articles/the-best-of-the-biggest-u-s-airports-1542204004?mod=ig_bestairports2018

McCuen, T. L., & Pittenger, D. M. (2016). *Building Information Modeling for Airports*. https://doi.org/10.17226/23517

MGI. (2013). Infrastructure productivity: how to save $1 trillion a year. *McKinsey Global Institute*, (January), 100. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Infrastructure+productivity:+How+to+save+$1+trillion+a+year#0

Ozorhon, B. (2013). Analysis of Construction Innovation Process at Project Level. *Journal of Management in Engineering*, Vol. 29, pp. 455–463. https://doi.org/10.1061/(asce)me.1943-5479.0000157

Petrullo, M., Morton, B., Jones, S. A., Laquidara-Carr, D., Lubrano, S., Lorenz, A., … Barnett, S. (2017). *The Business Value of BIM for Infrastructure 2017*. Retrieved from www.construction.com

Riitta, S., & Hirvensalo, A. (2008). Implementation of Building Information Modeling (BIM) – A Process Perspective. In R. Smeds (Ed.), *APMS 2008 Innovations in Networks Implementation* (pp. 379–386). https://doi.org/10.1063/1.3452236

Scapens, R. W. (1990). Researching management accounting practice: The role of case study methods. *The British Accounting Review*, *22*(3), 259–281. https://doi.org/10.1016/0890-8389(90)90008-6

Seale, C. (1999). Quality in qualitative research. *Qualitative Inquiry*, *5*(4), 465–478. https://doi.org/10.1177/107780049900500402

Sentence, A. (2013). *The new normal for airport investment*. Retrieved from www.pwc.com/capitalprojectsandinfrastructure

Shibeika, A., & Harty, C. (2015). Diffusion of digital innovation in construction: a case study of a UK engineering firm. *Construction Management and Economics*, *33*(5–6), 453–466. https://doi.org/10.1080/01446193.2015.1077982

Succar, B. (2009). Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in Construction*, *18*(3), 357–375. https://doi.org/10.1016/j.autcon.2008.10.003

Yin, R. K. (1994). Case Study Research Design and Methods. In R. K. Yin (Ed.), *Case study research Design and methods* (2nd ed.). https://doi.org/10.1017/CBO9780511803123.001

Building Automation System Data Integration with BIM: Data Structure and Supporting Case Study

Caroline Quinn[1], Ali Zargar Shabestari[2], Marin Litoiu[2] and J.J. McArthur[1,] *
[1] Department of Architectural Science, Ryerson University
[2] Department of Electrical & Computer Engineering, York University
* email: jjmcarthur@ryerson.ca

Abstract

Buildings Automation Systems (BAS) are ubiquitous in contemporary buildings, both collecting room condition, equipment operational data and sending control points developed by integrated sequences, but are limited by prescribed logic, possess only rudimentary visualizations, and lack broader system integration capabilities. Advances in machine learning, edge analytics, data management systems, and Facilitates Management Building Information Model software (FM-BIM) permit a novel approach to cloud-hosted building management. This paper presents an integration technique for mapping the data from a building Internet of Things (IoT) sensor network to an FM-BIM. The sensor data ontology and time series analysis strategies integrated into the data structure are discussed and presented, including the use of a 3D nested list to permit time-series data to be mapped to the FM-BIM and readily visualized. The developed approach is presented through a case study of an office living lab consisting of a local sensor network mimicking a BAS, which streams to a cloud server via a virtual private network connection. The resultant data structure and key visualizations are presented to demonstrate the value of this approach, which permits the end-user to select the desired timeframe for visualization and readily step through the spatio-temporal building performance data.

Keywords: FM-BIM, System Integration, Sensor data streaming, Internet of Things (IoT), Smart and Continuous Commissioning

1. Introduction

Parametric design tools, Building Information Models (BIMs), digital fabrication, and virtual construction scheduling generate a wealth of digital data on the built environment through the design and construction phases. As a building is put into operation, the magnitude of this information increases exponentially and FM-enabled BIMs (FM-BIMs) are of specific value in this digital context, having demonstrated time- and cost-savings benefits for soft (Arayici, Onyenobi, & Egbu, 2012) and hard facilities management activities (Volk, Stengel, & Scultmann, 2014; Love, Matthews, Simpson, Hill, & Olatunji, 2014; Arayici, Onyenobi, & Egbu, 2012; Bryde, Broquetas, & Volm, 2013). When Computer Aided Facility Management (CAFM) data is integrated into a BIM, this data provides significant benefits such as utility cost reductions, comfort management, space optimization, improved inventory management, and energy management (Love, Matthews, Simpson, Hill, & Olatunji, 2014). Over time, however, the volume of this information becomes extremely large and cumbersome, resulting in barriers to adoption associated with the level of effort necessary to maintain accurate BIMs and manage the information (Volk, Stengel, & Scultmann, 2014). BIM's are one of many "standalone information systems" used by building stakeholders. By creating integrations between systems (ex: IoT sensor network and FM-BIM), and working toward aggregating data in a single model, negative effects of standalone information systems can be minimized. A central FM-BIM is the system that should be built out to integrate to all building data sources, to be used through the building project and operational lifecycle.

To address the challenge of managing this information exchange, several researchers have developed strategies to integrate building information into FM-BIMs, including several who have used Dynamo or other visual programming languages to this end (Preidel, Daum, & Borrmann, 2017; Khaja, Seo, & McArthur, 2016; Gerrish, 2017). Others have developed ontologies to support data streaming to BIM using the Semantic Sensor Network (SSN) ontology (Kučera & Pitner, 2016). Once sensor data is available in the BIM it can be further integrated to other systems. COBie has been recommended for data integration from a BIM to a Computerized Maintenance Management System (Pishdad-Bozorgia, Gao, Eastman, & Selfa, 2018). There remains a paucity of literature regarding data streaming from sensor networks, as well as the type of summary information relevant to the FM-BIM (Kassem, Kelly, Dawood, Serginson, & Lockley, 2015). This research paper aims to fill this gap by presenting a complete IoT data acquisition, management, and BIM mapping ontology.

This paper presents a database architecture to facilitate the integration of IoT sensor data to an FM-BIM, effectively taking the first steps toward FM-BIM as a central data source for all building data. This paper further implements the proposed integration on a sensor data stream from a test-bed office, suggesting appropriate batch analytics and queries for the sensor data stream. Each of the sensor data streams are mapped to fields within the FM-BIM and using Dynamo sensor data values for desired time frames can be navigated. The research offers a database architecture which could act as the data source for cloud based SCCx through machine learning, as well as an accessible portal to BAS sensor related data typically hidden within a proprietary system. This would facilitate the creation of a full digital twin of a building in the form of an FM-BIM. Facility managers could use this model to test and plan maintenance projects, observe building conditions over time given outdoor conditions as well as system settings, retrieve specific sensor data using a visual interface, among other things. The next phase of this research will be scaling the architecture to a Smart Building level, as which point SCCx algorithms can begin to be explored and full building visualizations within the FM-BIM will be possible. Alternatively, future phases could include adding additional data integrations to FM-BIM.

2. Methodology

An IoT sensor data integration to FM-BIM requires three data processing components: (1) data acquisition and ingestion, where by the raw sensor data is collected and transferred to a cloud database; (2) batch analytics, a set of business rules to be executed on sensor data to summarize data for faster querying; and (3) integration, the querying process that summarizes data and maps to the appropriate FM-BIM fields. Figure 1 shows how these processes act on the various system elements (sensor points, database of historical records, and the FM-BIM).

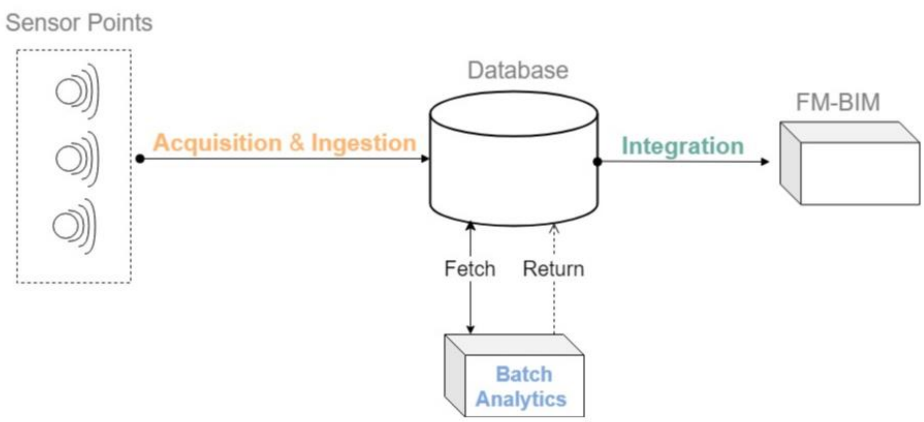


Figure 1: System architecture for IoT data streaming to FM-BIM*)*

2.1 Data Acquisition and Ingestion

In order to provide an efficient and flexible architecture minimal processing will occur during acquisition and ingestion. Data point values are organized in a hierarchical schema where the building is broken into successively more granular components . The hierarchy for a building would be: "building", which contains "systems", which have "elements", which have data collecting "points". For controls system mapping, relevant elements are assigned a Building Automation System Identifier (BASID), which may be either the equipment name or room number, depending on the element type. Each sensor point type is then assigned a PointID. The specific point assignments are based on a systematic review of the BAS schematics and controls sequences for the building. This hierarchical schema will result in each sensor being tagged with a human interpretable ID, allowing FM users to interpret the relevance of each sensor point to the building. Controllers periodically push data to a buffer which synchronizes the time series data of the points, this is a more efficient approach than synchronizing each data point stream directly in the buffer as the latter requires multiple network connections. The controller will allow data to be streamed more quickly from sensors to the FM-BIM, giving FM users a near live view of building operations (Ramprasad, et al., 2018). This process can be seen in Figure 2.

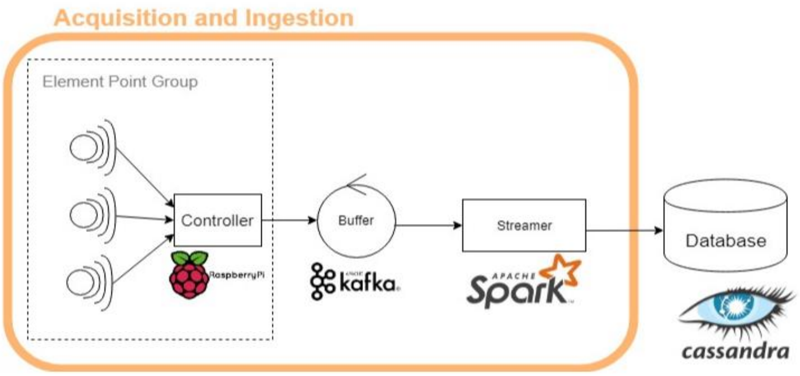


Figure 2: Data acquisition and ingestion process

Because a hierarchical data schema is used for integration of summarized point data to the FM-BIM, a variety of timestep granularities can be supported for visualization within the FM-BIM using aggregating run time queries. By decoupling individual points from the element group, batch analytics can run in parallel and therefore more efficiently.

2.2 Batch Analytics

Once raw data has been acquired and ingested to the cloud-based database centralized time series analytics can run in batch jobs to summarize data. Summarizing the data to single human readable metrics will mean less time spent by FM users interpreting building data. The cloud base environment is the appropriate place to run these analytics as it is a stable environment with high capacity and enough computational power to deal with high complexity summary calculations. Appropriate time series analysis methods depend greatly on the desired FM-BIM visualizations. Counts can be used as an effective means to visualize building deficiencies and therefore deficiency percent changes over time. Averages can be used to show conditions and system performance in a building, they can also be presented with their point value range for the selected timeframe. Figure 3 shows the general process using Spark for batch analytics.

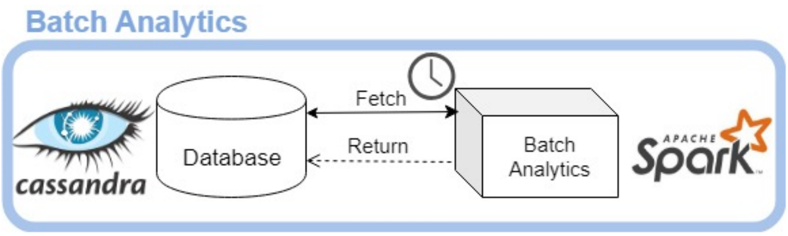


Figure 3: Batch analytics process

2.3 Integration

The data transfer from the database to the FM-BIM consists of three key steps:

1. For each visualization, a .csv file (format in Table 1) must be maintained from the summary tables that can be passed to the FM-BIM using a visual programming Language (VPL)(Dynamo) script. This file would be updated regularly as batch analytics are run with new incoming sensor data and saved with a fixed filename. This .csv file is a 2D list, columns headed with BASID and rows with timestamp, cells contain ordered comma delimited point values for the intersecting ID and timestamp.
2. The Dynamo script imports the .csv file, sorts it to match the FM-BIM element ordering and creates a 3D list by converting the ordered point values from a string to a list. Each index of the list contains a Revit element ID ordered list of point values.
3. The user selects the desired time for display in the FM-BIM using a slider, which inputs to a function that filters the transposed 3D list using a python script and outputs a 2D further transposed list of sensor data for each BASID at the specified timestep. This list is then mapped to the FM-BIM using the Dynamo Element.SetParameterByName node, updating the parameter in Revit of the element.

Table 1: Sample CSV format for BAS mapping to BIM (truncated)

	BASID1	*BASID2*
2019-04-24 17:00:00	*0.23, 22.3, 5*	*0.20, 24.3, 1*
2019-04-24 16:00:00	*0.22, 22.3, 0*	*0.23, 24.2, 1*

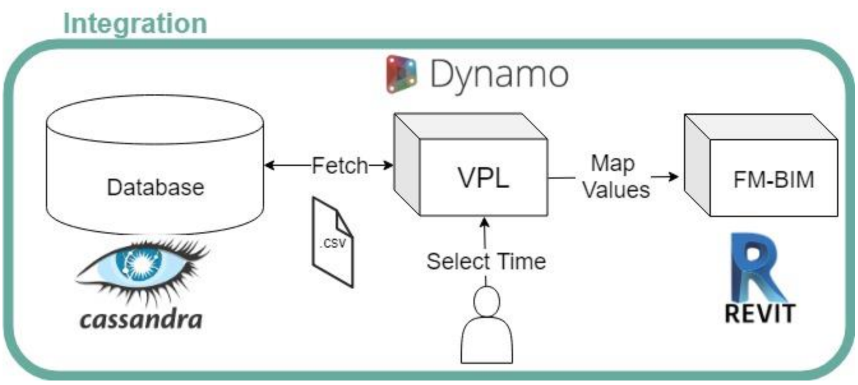


Figure 4: Database to FM-BIM integration process

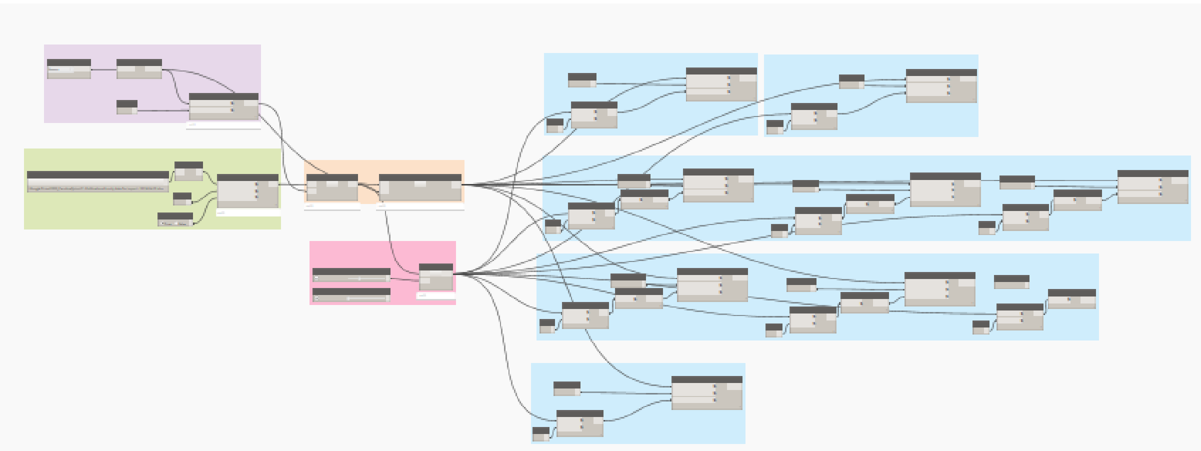
These .csv files can be used to map times series data such as averages or counts, a sample .csv can be seen in Table 1. A time slider to navigate over the time frame can be used to select data for mapping, for example a slider with values from 0-72 hours can be used to access average point (sensor) values in the past 72 hours. These are shown in the BIM, giving FM users a visual and interactive platform to interpret sensor data. Furthermore, daily averages or counts can be mapped for monthly trend visualization using a less granular slider that ranges from 0-30 days, or monthly averages or counts for annual or seasonal visualization with. Figure 5 shows the Dynamo implementation for hourly navigation. The code for creating the 3D list of inputs for mapping is as-follows:

```
    import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *
importList = IN[0] # the main list imported from excel
elementList = IN[1] # the list of elements in revit
newList = []
for i in range(1, (importList[0])):
    for j in range(0, len(elementList)):
```

```
            if elementList[j] == importList[0][i]:
            element_to_add = []
            element_to_add.append(importList[0][i])
            for k in range(1, len(importList)):
                tuple_to_add = []
                tuple_to_add.append(importList[k][0])
                temp = importList[k][i].split (",")
                for z in range(0, len(temp)):
                    tuple_to_add.append(temp[z])
                element_to_add.append(tuple_to_add)
            newList.insert(i-1, element_to_add)
            break;
        else:
            continue
OUT = newList

    import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *
elementList = IN[0]
ImportList = IN[1]
newElementList = []
for i in range(0, len(ImportList)):
    for j in range(0, len(elementList)):
        if (ImportList[i][0] == elementList[j].GetParameterValueByName("Number")):
            newElementList.insert(i, elementList[j])
    else:
        continue
#Assign your output to the OUT variable.
OUT = newElementList
```

Top:



Bottom:

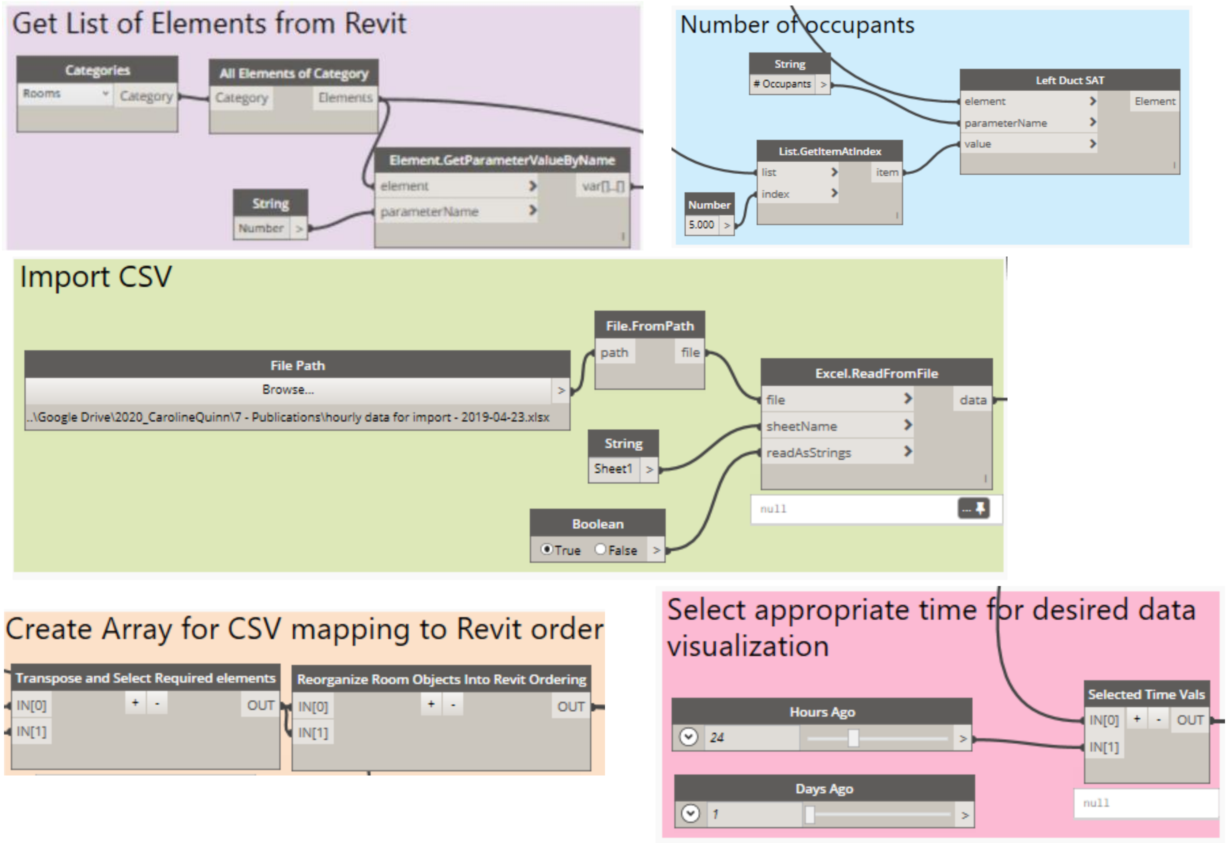


Figure 5: Dynamo script for time-specific data mapping: (top) high-level summary showing node relationships; (bottom) individual code blocks)

The code for selecting the time is as-follows:

```
    import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *
allData = IN[0]
selectedTime = IN[1]
valsToMap = [[] for _ in range (len(allData[0][1])-1)]
for j in range (0, len(allData)):
    for k in range (1, len(allData[0][int(selectedTime)])):
            valsToMap[k-1].insert(j , allData[j][int(selectedTime)][k])
OUT = valsToMap
```

Note that the scripts presently do not support null point values as this causes data type errors within the Dynamo and therefore a large dummy value must be inserted for any missing data points. Future work will implement the necessary logic to permit null value mapping so that sparse matrices of point value data can be handled, as these are computationally the most efficient for data storage.

3. Case Study from an Office Living Lab

A living lab test cell has been established within a single faculty office, which incorporates a local sensor network. Sensors measuring occupancy, lighting state, door position, and HVAC are integrated with an Arduino Mega 2560 and streamed via an Ethernet connection to a private cloud. Other systems in this office but not discussed in this paper measure ambient temperatures in the office and adjacent spaces (direct cloud streaming) and thermocouples for surface temperature measurement. Figure 6 shows sample instantaneous data accessible through a web interface.

Ryerson (ryerson)

Timestamp	values
2019-04-25 13:28:12	occupancy: 1 lights: 1 doorPosition: 1 airVelocity_left: 10.87 airVelocity_right: 1061.07 humidity_left: 50.20 temperature_left: 21.50 humidity_right: 47.10 temperature_right: 24.20

	A	B	C
1	timestamp	ARC-0309	ARC-0314
2	'14-Mar-2019 19:44:00'	0.2,0.2,0.1,12.1,36.2,20.8,34.6,24	0,0,0,10.4,33.1,20.4,33.8,22.6
3	'15-Mar-2019 19:44:00'	0,0,0,18.7,41.9,18.9,35.3,23	0,0,0,10.6,56.5,18.9,43.7,23.5
4	'16-Mar-2019 19:44:00'	0,0,0,12.4,26.3,20.9,27.7,23.3	0,0,0,10.9,36.5,20.2,34.6,23.5
5	'17-Mar-2019 19:44:00'	0,0,0,11,21,21.2,23.8,23.6	0,0,0,10.9,45.4,19.7,38.4,23.5
6	'18-Mar-2019 19:44:00'	0.1,0.1,0.1,10.9,26.6,20.6,27.4,23.6	0,0,0,10.9,48.9,19.1,40,23.7
7	'19-Mar-2019 19:44:00'	0.3,0.3,0.2,13.4,30.4,20,29.7,23.4	0,0,0,11,21,21.2,23.8,23.6

Figure 6: Sample screenshot from live streaming of office data to the cloud (top) and pre-processed daily average CSV rows (bottom); the highlighted data is mapped in Figure 7

This sensor data has been mapped to an FM-BIM for the host building, created in Revit 2019. This model uses the room number as the BASID as in this simplified case, all sensors are room-mounted. ARC-309 is the sensor test room showing actual data; dummy data has been populated into another room on the same floor (ARC-314) for visualization purposes. The Dynamo script presented in Section 2 has been integrated with this FM-BIM and visualizations of the daily average sensor data for two sample days are shown in Figure 7.

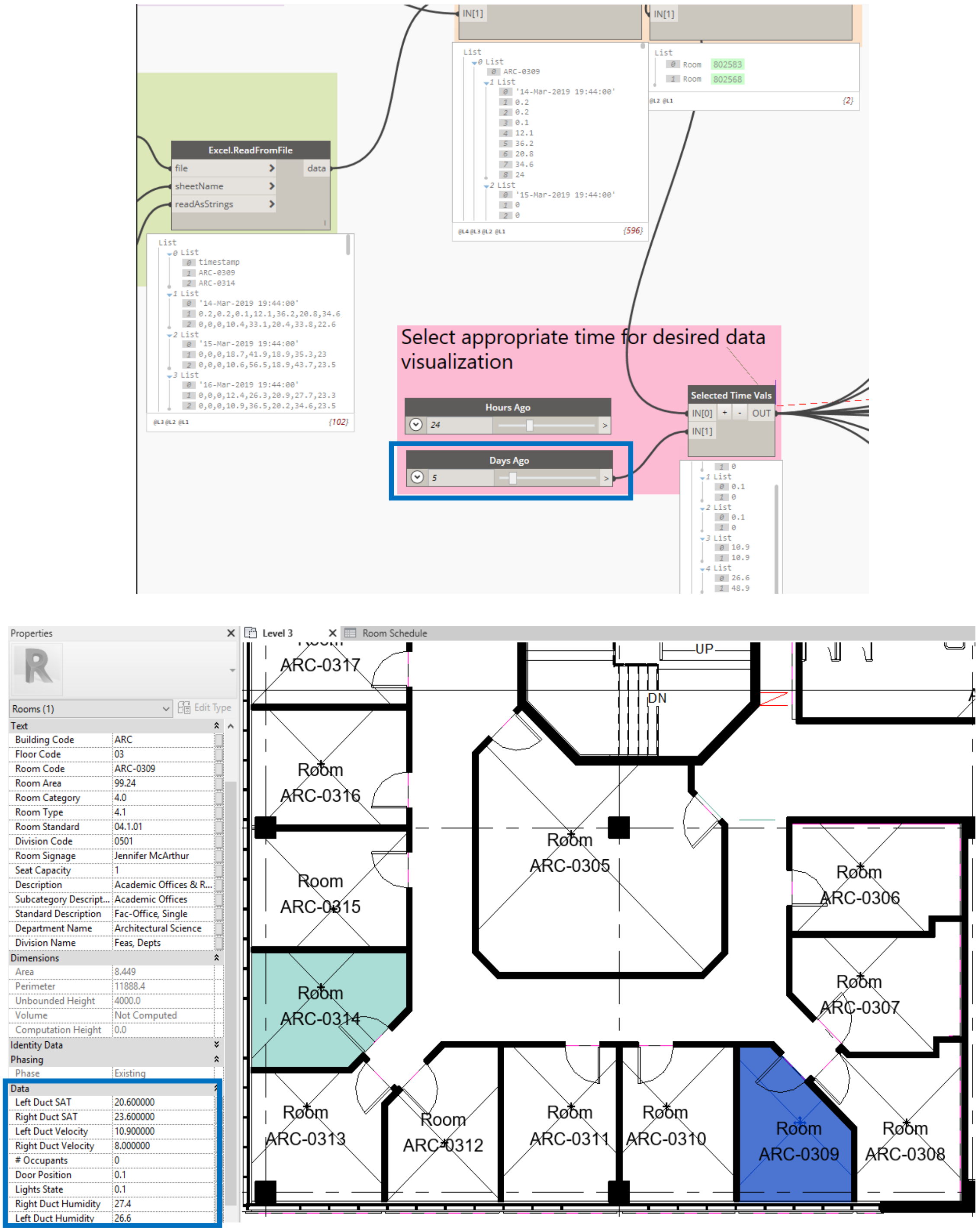


Figure 7: Top: Dynamo slider set to "5 days ago". Bottom FM-BIM showing daily average BAS sensor data mapped from March 17th, 2019 19:44 – March 18th 2019 19:44

4. Discussion and Conclusion

BAS data is highly valuable within an FM-BIM, however due to the high measurement frequency, the supporting database architecture and data visualization must be carefully considered in order to facilitate BAS to FM-BIM integration. This paper presents a database architecture that allows for high-frequency low-latency data transmission by using sensor point controllers, dedicated database buffers and streamers, a cloud-based database, and batch analytics. This architecture permits efficient summarization of heterogeneous BAS data on the cloud where scalable computational resources are available. The data summarization techniques proposed include averages and counts on an hourly, daily, and monthly basis. Consistent with building energy modeling norms, data regarding occupancy or lighting state are indicated in real time as integers, however these must be stored as floats for hourly, daily, and monthly averages to better reflect the percentage time that a space is occupied or illuminated. The summarization of sensor data using this method allows the FM-BIM to be the single building data model for FM users to consult during the operational life of a building, while maintaining a data structure that can also be used by building applications for energy management and other building controls.

The use of Dynamo, a VPL, was found to be highly effective in mapping time series data integration from a .csv file to an FM-BIM, provided proper structure. The presented format contains sensor data for each point as a string to form a tuple, which is then inserted into a 2D list with time in rows and BASIDs in columns to create a 3D list with indices of time, BASID, and point values. From this list, sub-arrays mapping BASID vs POINTID can be accessed for a given time using the slider and code presented. This study has been limited to room-hosted data points and a more complex mapping algorithm will be required to update both room-hosted and element-hosted time-series data, as the existing script can only map to a single element type at once. An additional limitation of this work requiring further development is that null values cannot be processed by the script; as a temporary solution, a dummy value (555555) has been substituted for missing data, but code refinement is necessary in future work to overcome this limitation. This will reduce the computational cost by permitting the use of spare matrices for data storage.

This work has yet to be scaled to the full-building or tested by facility-users and this scaling and testing will form the long-term future work in this field. In addition, incremental functionality will be developed to enhance the analytics to integrate deficiency alarms using the trended data as defined in accordance with ASHRAE Guideline 36-2018 High Performance Sequences of Operation for HVAC Systems (ASHRAE, 2018). A more refined graphical user interface should be developed, were users can interact with sliders outside of the VPL to initiate IoT sensor data integration with an FM-BIM. Further work on defining relevant BAS data summarization techniques should be done in collaboration with end-users such as Facility Engineers. Topics for consideration include additional measures to be mapped, for example data maxima and minima, different timeframes, and dashboard integration.

Cyber physical systems are concerned with the feedback loop of sensing, evaluating, and acting on building conditions (Schmidta & Åhlund, 2018). Schmidta describes building automation as a three-layer architecture facilitating this feedback loop. This research focuses on making the bottom layer of this architecture- the field level comprised of sensors and actuators- available to the top layer – the management level comprised of building management system and visualizations tools-while maintaining the ability to engage the middle layer where applications such as predictive control are applied. Most current research in cyber physical systems focuses on optimizing operational energy cost or consumption (Schmidta & Åhlund, 2018) through the development of the middle layer. However, sensor data visualization should be considered and further researched in cyber physical systems. The middle layer is not easily interpreted by FM users, and without a thoroughly developed top management layer there will be a loss of agency for FM users as cyber physical system development progresses. This is increasingly important for cyber physical systems with tightly coupled sensing and actuating embedded systems as described by Kleissl & Agarwal (2010) where there is no discussion of visualization at the management level.

This research lays the foundation for a long-term project to develop a cloud-hosted BIM-integrated FM platform, permitting data analytics with complex predictive modeling and classification algorithms to support applications such as Smart and Continuous Commissioning and Model Predictive Control. The visualization of the summarized sensor data provides an integrated view for facility managers and building operators to support integrated asset management and optimization.

Acknowledgements

This research was financially supported by the BRAIN Alliance - Big Data Research, Analytics, and Information Network, funded by the Ontario Research Fund Centres of Excellence program and FuseForward.

References

Arayici, Y., Onyenobi, T., & Egbu, C. (2012). Building Information Modelling (BIM) for Facilities Management (FM): The Mediacity Case Study Approach. *International Journal of 3-D Information Modeling, 1*, 55-73.

ASHRAE. (2018). ASHRAE Guideline 36-2018: High Performance Sequences of Operation for HVAC Systems. Atlanta: American Society for Heating, Refrigeration and Air-Conditioning Engineers.

Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of building information modelling (BIM). *International Journal of Project Managmeent, 31*(7), 971-980.

Gerrish, T. (2017). *Exploring the effectiveness of BIM for energy performance management of non-domestic buildings (Doctoral dissertation)*. Loughborough: Loughborough University.

Kassem, M., Kelly, G., Dawood, N., Serginson, M., & Lockley, S. (2015). BIM in facilities management applications: a case study of a large university complex. . *Built Environment Project and Asset Managemen, 5*(3), 261-277.

Khaja, M., Seo, J. D., & McArthur, J. J. (2016). Optimizing BIM Metadata Manipulation Using Parametric Tools. *Procedia Engineering, 145*, pp. 259-266. Tempe.

Kleissl, J., & Agarwal, Y. (2010). Cyber-Physical Energy Systems:. *Design Automation Conference* (pp. 749 - 754). Anaheim: IEEE.

Kučera, A., & Pitner, T. (2016). Semantic BMS: Ontology for Analysis of Building Automation Systems Data. In L. M. Camarinha-Matos, A. J. Falcão, N. Vafaei, & S. Najdi (Ed.), *7th Doctoral Conference on Computing, Electrical and Industrial Systems (DOCEIS)* (pp. 46-53). Costa de Camperica, Portugal: IFIP Advances in Information and Communication Technology. doi:10.1007/978-3-319-31165-4_5

Love, P., Matthews, J., Simpson, I., Hill, A., & Olatunji, O. (2014). A benefits realization management building information modeling framework for asset owners. *Automation in Construction, 37*, 1-10.

Pishdad-Bozorgia, P., Gao, X., Eastman, C., & Selfa, A. P. (2018). Planning and developing facility management-enabled building information model (FM-enabled BIM). *Automation and Construction, 87*, 22-38.

Preidel, C., Daum, S., & Borrmann, A. (2017). Data retrieval from building information models based on visual programming. *Visualization in Engineering, 5*(1), 1-14.

Ramprasad, B., McArthur, J., Fokaefs, M., Barna, C., Damm, M., & Litoiu, M. (2018). Leveraging existing sensor networks as IoT devices for smart buildings. (pp. 452-457). Singapore: IEEE 4th World Forum on Internet of Things (WF-IoT).

Schmidta, M., & Åhlund, C. (2018). Smart buildings as Cyber-Physical Systems: Data-driven predictive control. *Renewable and Sustainable Energy Reviews*, 742-756.

Volk, R., Stengel, J., & Scultmann, F. (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction, 38*, 109-127. doi:http://dx.doi.org/10.1016/j.autcon.2013.10.023

A Framework for Improving Business and Technical Operations within Timber Frame Self-Build Housing Sector by Applying an Integrated VR/AR and BIM Approach

Lilia Potseluyko[1] and Farzad Pour Rahimian[2*]
[1]Faculty of Engineering, University of Strathclyde, Glasgow, UK
[2]School of Science, Engineering and Design, Teesside University, UK
[*]email: f.rahimian@tees.ac.uk

Abstract

Timber Frame Self-Build Housing Sector (TFSBS), accounts only to 7-10% of the UK's housing construction market. This figure is significantly higher in some other contexts, e.g. 80% in Austria, 60% in Canada and 50% in the USA. With the government's policies stepping in to encourage self-building, it is essential for the companies to increase their competitiveness providing an efficient workflow and clear communication with the clients by using the latest digital technologies. End-users, who make buying decisions to self-build, often have little or no knowledge of the construction industry. Therefore, they face significant challenges in communication with professionals in terms of spatial awareness, ability to visualise technical drawings and understanding the construction process. For many architectural and construction practices in the UK's TFSBS, the primary communication medium with clients is email. This results in an increased number of the iterations per each project lifecycle, leading to difficulties in interoperability among designers, manufacturers and builders. Virtual and Augmented Reality (VR and AR) technologies are widely acknowledged as aids for clients and professionals in a more productive interaction. Game technologies have also been recognised to be effective in resolving problems in science and business. However, designing data-rich Virtual Reality Environments (VREs) that would enhance clients' spatial understanding from the solution spaces, simplify architect-client business/marketing communications, provide parametric customisation options, consolidate quantification, support interoperability, and leverage integration across the whole BIM process are still outstanding challenges. Business and technical key performance indicators, as well as conceptual and methodological frameworks, are developed for adopting BIM principles and emerging game-like VR and AR technologies to support TFSBS within the UK housing industry in Business and Technical Operations. This paper concludes with technical recommendations for the development of a proof of concept prototype to support the aim as mentioned above.

Keywords: Building Information Modelling, Timber Frame, Self-Build Housing, Interoperability, Virtual Reality

1. Background of the study

Majority of residential property buyers in the UK consider self-building route as an alternative to mass production development options. Bespoke houses in chosen locations also appeal to clients with an opportunity to save up to 30% on market value or optimise budget use, equip the house with high energy efficiency level and latest home technologies. Clients who undertake a self-build project would typically need to accomplish following tasks: finding a plot, agreeing on house design, cost calculation, attaining planning and building regulations permissions, deciding on finance, project management and others. The Timber Frame Kit Home Manufacturing Companies (TFKHMC) are one of the critical service providers in the sector, who offer a packaged range of services, which frequently include: conceptual and technical design, cost optimisation solutions, assistance in attaining relevant planning and building permissions, kit home manufacturing, shipping kit homes to the construction site, customer service and other forms of consultancy (Banihashemi *et al.*, 2017).

Despite multiple benefits, UK TFSBS is relatively small compared to its European and North American counterparts. The number of self-build projects per year in the UK fluctuates steadily between 10000 to 15000 items and accounts only to 7-10% of the UK's housing construction market, whilst this number reaches 80% in Austria, 60% in Canada and 50% in the USA, with the other countries having similar dispersion (Wilson, 2017). The macro-level of the stagnation factors in the UK is a culture of the supply chain not being customised enough to cater to individual home builder's demands, difficulty in acquiring the land by individuals versus big house developer companies and educating the market about the process of the self-build. The micro-level of the problem in UK TFSBS, as well as worldwide, is the enabling effective communication process between client and TFKHMC. Technical drawings and 2D images are frequently insufficient for clients with no construction background to visualise their future builds, decide on details and extensions needed. These results in an increasing number of the iterations per each project lifecycle, having difficulties in keeping all the records in one consistent source and passing accurate information to manufacturers and builders.

With the new governmental incentives directed on raising the profile of the sector, it is essential for TFSBS Companies to reach out for the potential clients, encourage and educate them in several benefits self-build option could offer and simplify the process of self-build for the clients. Virtual and Augmented Reality (VR and AR) technologies are widely acknowledged as aids for clients and professionals in a more productive interaction. Game technologies have also been recognised to be effective in resolving problems in science and business (Hackl and Wolfe, 2017; Kandaurova and Lee, 2018).

Therefore, the focus of this study is designing data-rich VREs that would enhance clients' spatial understanding from the solution spaces, simplify architect-client business/marketing communications, provide parametric customisation options, consolidate quantification, support interoperability, and leverage integration across the whole BIM process are still key challenges. Figure 1 explains the focus of this study, which is bringing together of Architecture/Engineering/Construction (AEC) industries with the Computer Science and Electronic&Electrical Engineering (EEE) in order to integrate openBIM, AR/VR/MR, and Gamification for helping and supporting UK TFSBS sector.

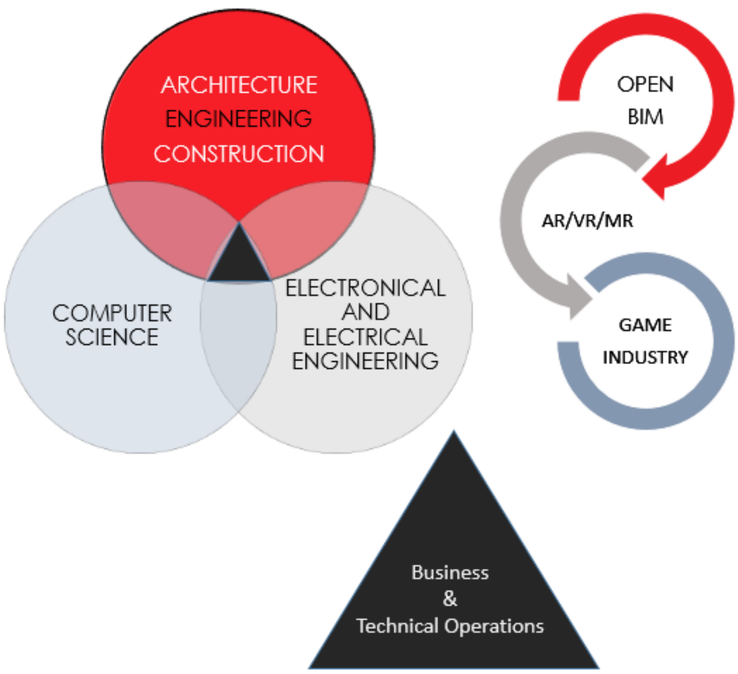


Figure 1: The Study Focus

2. BIM Principles Implementation with the help of VR/AR/MR Technologies

With the very few existing studies focusing on the application of BIM and Virtual Reality (VR) technologies in TFSBS (Pour Rahimian *et al.*, 2019), this paper has explored the broader subject of BIM and VR (as reported in: Boton, 2018; Chalhoub and Ayer, 2018; de Klerk *et al.*, 2019; Heidari *et al.*, 2014; Sun *et al.*, 2017).

The Idea of Virtual Showroom has been conceptualised for decades and been reported in several studies (Abdelhameed, 2013; Rahimian and Ibrahim, 2011; Yu, 2011), however previously scholars pointed out factors related to the existing hardware and software limitations. In the last couple of years (2017-2018) rapid growth in the application of gaming technologies in the AEC sector, development of BIM interoperability and EEE have enabled a new chain of available capabilities in visualising high fidelity virtual spaces. This progress in technology requires a new sequence in the exploration of the idea of Virtual Showroom.

Several studies focused on the application of VR in BIM to resolve the complexity of dealing with federated models: VR has attracted increasing attention of the AEC and Facility Management (AEC/FM) industry in recent years, as it shows a great potential to improve workflow efficiency through enhanced common understanding (Du *et al.*, 2018). One of the examples of property management using VR technologies focuses on room views influence on apartment prices. To assess such an influence, a virtual experiencing and pricing method for room views based on BIM and oblique photogrammetry was proposed by Sun *et al.* (2017).

Huge progress has been made on ‘Augmented Reality’ (AR) techniques such as registration, tracking, and display hardware. However, a construction AR system should be more convenient and combined with in-use applications to support multi-disciplinary users throughout the construction lifecycle (Solihin *et al.*, 2017). In an industrial environment, where strategic decisions are to be made, to create aesthetically beautiful experiences is unless specific applications such as design or perceived quality (only) a plus. What is needed is to have reliable systems upon which one can rely on a development process. The developers need to make sure that an engineer will be able to work with a digital mock-up with as much performance as needed (Perroud *et al.*, 2017).

Few other researchers emphasised the need for collaborative and multi-user VR experiences in construction and architectural design. Scientists experimented with conceptual prototyping design, the flow of data from an authoring tool to visualisation environment as well as participatory decision making (de Klerk *et al.*, 2019; Du *et al.*, 2018; Sanchez-Sepulveda *et al.*, 2019). This paper has analysed the research mentioned above, and the findings are presented in the Framework.

3. Business Operations Implementation with the Help of VR/AR/MR Technologies

The seminal literature has reported on the subject of communicating design intent between an architect and a client and presenting outcomes in the form of a winning bid (Sawczuk, 2013). Large architectural projects are expected to have extended project lifecycles and planning stages; as a large number of stakeholders are involved. Conversely, small scale residential projects require significantly shorter project cycles and faster interoperability workflows reaching out clients often remotely.

To examine the subject of business operations in TFSBS applying VR technologies authors have investigated a broader range of VR applications.

Several scholars addressed the use of immersive virtual reality technologies in virtual simulated stores, museums or archaeological sites and its correlation with enhanced presence and usability compared to conventional desktop technology (Goulding *et al.*, 2012). The studies showed the use of immersive technologies resulted in improved presence and usability; however, admitted the need for further advancement in VR hardware and software capabilities.

Another study conducted by Fang *et al.* (2014) proposed the mechanisms to enable reputation building for e-commerce in VR. They stated that people are becoming more willing to shop online rather than going to traditional shops. However, current e-commerce systems only provide users with a simple browser-based interface to acquire details of products and services. VR experiences allow buyers to model trustworthiness of sellers and distinguish honest sellers from malicious ones. Showroom sales process characterised by creating a specific environment that enhances the sale. The factors that boost showroom sales include lighting, sound and ability to interact with an object to test (de Wijk *et al.*, 2018).

Haller (2017) examined underlying universal colour patterns in interior design that everyone responds and a combination of colour evoking certain emotions. The study conducted by Sherman and Craig (2018) emphasises the equal necessity for a comprehensive exploration of the VR subject area as well as the VR medium. Wide range of VR applications subjects in the research conducted, includes military training, education and design. Authors draw attention to the fact that adoption of VR in each area must be driven by deliberate design, design to engage the audience, social interaction consideration, understanding user objective, start, process and end of the game scripts and need for tradeoffs.

Lin *et al.* (2017) conducted on clients' feedback on VR product configurator use. The empirical evidence appears to confirm the notion that the VR system of product configurator enables a better understanding of the future product and hence reduces indecision/objection handling stage during the sales process. Kandaurova and Lee (2018) studied VR effects on empathy and the level of donation for charitable giving. Scientists have found evidence VR experiences boosts the level of empathy and social responsibility, which manifests in a high level of monetary donations and intention to volunteer.

In-person sales are one of the most effective sales tools as it engages all channels of communication: verbal, the intonation of the voice, opportunity to use sales visuals, expressive body language and demonstrations. Various publications and authors have focused on identifying critical stages of successful sales. Immersive VR software as a sales tool should adopt the principles of the essential buyer-seller steps in the in-person sales process.

4. Game Technologies

The quality of VR experience is often recognised via two characteristics: a sense of presence and sense of immersion (Jarald, 2014). Whilst immersion is about the characteristics of technology, presence is an internal psychological, and physiological state of the user. There is a large number of factors that contribute to the quality of virtual experiences (Jarald, 2014; Paes *et al.*, 2017). Although a substantial number of studies focused on improving the effectiveness of operational processes in the construction industry, there also a pool of studies in storytelling in Virtual worlds for marketing and sales. However, the few researchers focused on the integration of both areas of knowledge.

The exponential growth of VR in applications across various platforms has been depicted in multiple statistic sources and events. Nevertheless, mainstream customers appear to be relatively uninformed of existing VR/AR channels as a medium for sales. To narrow the gap in experiencing VR as sales channel, the current generation of VR developers should consider the needs of first-time VR users, evaluating needs for introduction videos, lighter interface versions and also multi-user VR experiences, where one of the participants would act as a guide through virtual environment as well as the possibility of voice-controlled interface. Further studies should be implemented to examine the effectiveness of each interface component to aid first time VR Users;

Multiple researchers and developers have emphasised optimal hardware requirements for comfortable VR experiences, including Graphics Card and GPU ranges, which would be facilitating high frame rate; as well as specific headset brands and new market trends for wireless VR hardware. With the hardware market steadily improving, larger volumes of high fidelity data could be visualised in VREs. For the current study, all elements of a VREs could be subdivided into four main groups: (1) Essential AEC data that has been predefined in a vendor software and exported into VE; (2) Visual objects that have been added by various sources to set the scene, e.g. example interior design; (3) Existing VR interface and programmed sales logic; (4) Effects and others, including lighting, particles, render and audio effects.

The essential part of this research included empirical studies of existing VR interfaces. This study has interacted and analysed a number of existing VR experiences, among them:

- AEC focused interfaces;
- Creative art and sculpturing experiences;

- Guided virtual tours experiences;
- Scientific visualisations;
- Virtual stores;
- VR Games.

The advantages and drawbacks of applicability to the study have been classified in discussed in the Framework section.

5. Framework

The available functionality needs to be examined for serving sales purpose and not deriving client from it. It is a general game purpose to entertain. However, the scope of the research is to identify only functionality that would sell the product at the end of the iteration. VR software should be considered as a part of the company sales process and fit seamlessly into company workflow.

Understanding the stage of the client's journey is paramount in determining the required functionality. Three forms of client interactions were identified in this study: (1) First point of contact, (2) Option Selection, (3) Final Inspections. The exclusive approach was offered for each form of interaction.

The first point of a company communication with a client is characterised with building the rapport, establishing company credibility and familiarisation with the multitude of the product range. Therefore for the clients, who just considering the self-build option, are recommended to use a lighter version of the VR experience. 360 images and videos, WebVR experiences are now fairly easy to be accessed through brand mobile apps and company websites. HTML frameworks like A-Frame and Roundme provide easy deployment of Interactive WebVR experiences on any website. Branded cardboard headsets could be posted to a client location for further encouragement. The 360 scenes with gaze interaction interface enabling the transition from one image to another are sufficient to fulfil the first point of contact communication stage with the client: high fidelity spatial perception demonstration, reputation building, quick access to a multitude of the product demo scenes. At the current level of hardware and software capability, lightweight 360 scenes have proven to be more efficient, compare to heavyweight 3D scenes, which would need to incur significant optimisation or loss of the level of the detail and visual quality to be adapted for WebVR.

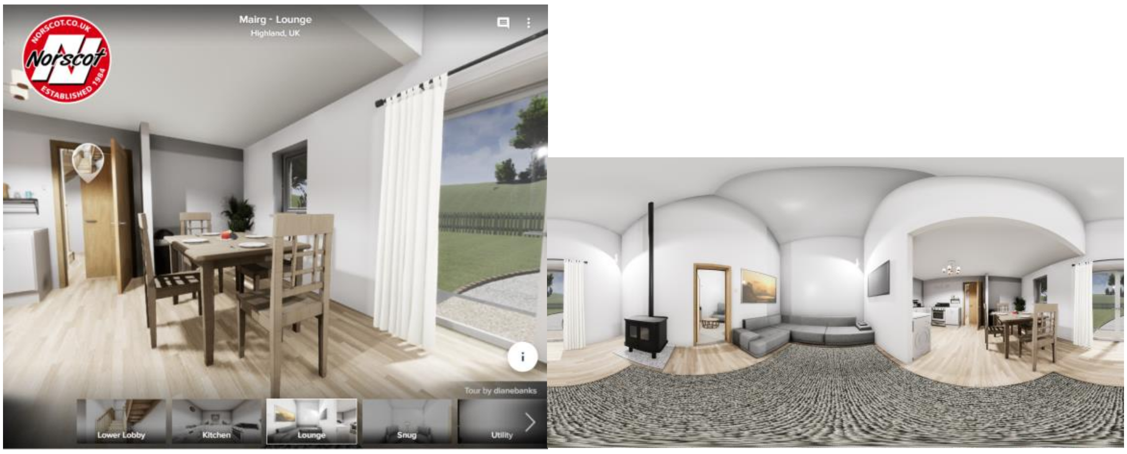


Figure 2: 360 Architectural Scenes Demostration for Web and Mobile Platforms. From Left to Right: (1) Lounge Demonstration, (2) Unwrapped 360 image of the same room

Once company credibility and reputation are demonstrated, and a client has committed working with a specific company, the next stage - **option selection** would require much more detailed functionality. Possible amendments discussed at this stage will include plot geography-related design adjustments, wall extensions, client personal preference plan amendments, doors and windows positioning and styles. A client's decision motives on preferred design would typically include available budget, plot location, size and geographical parameters, estimated completion timescale, design energy saving estimates, lifestyle and room functionalities, furniture content, necessary disability adjustments, aesthetic preferences, etc.

Summarising the above research and with the current level of hardware and software development, following virtual reality functionality was proposed for the stage:

- **Landscape visualisation**. The available plot location and size are crucial factors influencing design choice, vertical and horizontal spread, rotation depending on views, sunset and sunrise positions, energy efficiency and daylight optimisation. Among the pool of the technological solutions for landscape visualisation following options were considered: downloadable 3D maps, 3D landscapes obtained from various geographical databases, scanned point cloud data. Due to budget and time constraints for each self-build project in the optimal solution of 360 photographs of the construction site were offered. Carefully aligned 360 photographs of a plot placed into VR along with the design provide a basic understanding of a future build position and location. At further client request and available budget, more detailed landscape visualisation could be provided. Interactive day and night cycle functionality was offered.

- **Floor plan visualisation**. Due to not having any technical background, many clients have difficulty to visualise technical drawings and floor plans. Establishing a connection in VR environment with the existing floor plan will help clients to navigate with ease and quickly locate the zones that require changes. Authors have studied a number of architectural walkthroughs and gaming experiences. Among options tested were: (1) motion-controller-attached 2D floor plan with teleport locations, (2) location-based menus with images of teleport options and return button, (3) minimap, which demonstrates real-time location on the floor plan and option to return to the start, (4) scroll menu with room names and teleport destinations. The scroll menu appeared to be the easiest in terms of creation of speed workflow and reusability for each new scene. However, it was the least effective for giving the clients perception of space. On the contrary minimap as frequently used gaming directions tool appeared to be most effective for providing understanding the link between the floor plan and virtual space. The Return to the Start Button was agreed to be effective for many users to restart the journey.

Figure 3: Floor Plan Visualisation. Left to Right: Floor Plan Attached to Left Controller; Reusable Teleport Buttons System; Aligned Floor plan.

- **Interior Swaps**. With a number of VR game experiences tested and analysed, this paper concluded that the individual object and material swaps appear to be time consuming and ineffective. Instead, batch interior swaps were offered. When entering an empty room, a user was presented with a selection panel options of standard interior presets, e.g. converting each room from single to double bedroom, to a nursery and to study. Natural colours and standard furniture sizes would enhance spatial perception and give clients directions if there is a need for design extensions.

Figure 4: Visualising Room Sizes. Left to Right: Choosing Furniture Size; Choosing Interior; Changinge Door styles.

- **Quantification and Product Range Demonstration**. Virtual Space is an ideal environment for demonstration of additional product range, including elements like doors and window styles. Frequently, the main criteria for selecting either option is aesthetic preferences and a price difference. Architectural software packages like Revit are ideal tools for quantifying all elements and their options. However, for Virtual Reality users, it would be too time-consuming and overwhelming to expect an update for every door and window style and price change. The game engine functionality is successful in bringing the database information and coding available total estimated savings depending on choosing either option. As an example, The Door Sales Logic was scripted and demonstrated for the clients. Automated Python scripts were used inside the game engine to swap Revit exported doors to Game Door Actors with scripted behaviour and price. Selecting a particular door style, would change the doors according to it and give an update to total price change.

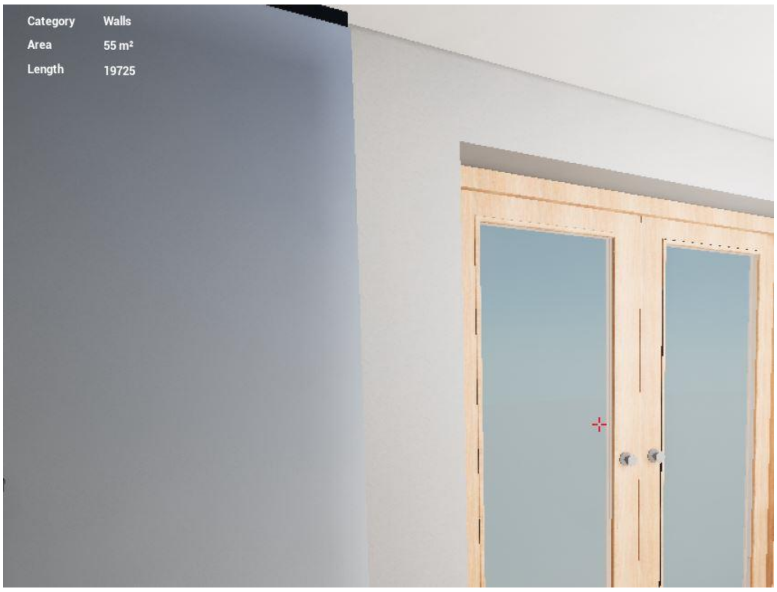


Figure 5: Quanitification Demonstration.

Thirdly, the final stage for client-designer/salesperson interaction in VR is the final check and approval. Once a client has agreed on all the adjustments and options, it is essential to have the functionality of saving the game and printing out the final bill of quantities for a client to sign.

6. Conclusion

The aim of this paper was to review existing literature on the implementation of BIM, VR and AR technologies and assess their applicability to TFSBS. The number of published scientific works on the VR/AR/MR in construction registered exponential growth in the last five years. The classification and content analysis of the literature revealed a few trends and gaps in this subject. This study achieved the mentioned aim by suggesting applicable directions for software development.

The Virtual Reality Experiences for TFSBS are characterised by shorter, and more repetitive workflows compare to other real-time architectural visualisations for bigger projects. Therefore the proposed framework is more focused on templates creation rather than providing accurate detail for each specific project. There is a major discussion still active in understanding which functionality is effective in-game environment or predefined in architectural software. The future research agenda will focus on parametric amendments inside the game engine and updating architectural software accordingly, further exploration of navigation aids with the voice-controlled interface and multi-user functionality.

Acknowledgements

The authors wish to gratefully acknowledge the generous funding received from InnovateUK, Norscot Joinery Ltd to support this study as a part of the Knowledge Transfer Partnership hosted by the University of Strathclyde, Glasgow. The authors also would like to acknowledge contributions of all people involved in this study, especially Dr Ian Heywood (Knowledge Transfer Adviser, InnovateUK) and Jason Fraser (Technical Operations Manager, Norscot Joinery Ltd) for providing Business and Technical Guidance.

References

Abdelhameed, W. A. (2013). Virtual Reality Use in Architectural Design Studios: A Case of Studying Structure and Construction. Procedia Computer Science, 25, 220-230. doi:https://doi.org/10.1016/j.procs.2013.11.027

Banihashemi, S., Tabadkani, A., & Hosseini, M. R. (2017). Modular Coordination-based Generative Algorithm to Optimize Construction Waste. Procedia Engineering, 180, 631-639. doi:https://doi.org/10.1016/j.proeng.2017.04.222

Boton, C. (2018). Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation. Automation in Construction, 96, 1-15. doi:https://doi.org/10.1016/j.autcon.2018.08.020

Chalhoub, J., & Ayer, S. K. (2018). Using Mixed Reality for electrical construction design communication. Automation in Construction, 86, 1-10. doi:https://doi.org/10.1016/j.autcon.2017.10.028

de Klerk, R., Duarte, A. M., Medeiros, D. P., Duarte, J. P., Jorge, J., & Lopes, D. S. (2019). Usability studies on building early stage architectural models in virtual reality. Automation in Construction, 103, 104-116. doi:https://doi.org/10.1016/j.autcon.2019.03.009

de Wijk, R. A., Maaskant, A. M., Kremer, S., Holthuysen, N. T. E., & Stijnen, D. A. J. M. (2018). Supermarket shopper movements versus sales and the effects of scent, light, and sound. Food Quality and Preference, 70, 32-39. doi:https://doi.org/10.1016/j.foodqual.2017.03.010

Du, J., Zou, Z., Shi, Y., & Zhao, D. (2018). Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making. Automation in Construction, 85, 51-64. doi:https://doi.org/10.1016/j.autcon.2017.10.009

Fang, H., Zhang, J., Şensoy, M., & Magnenat-Thalmann, N. (2014). Reputation mechanism for e-commerce in virtual reality environments. Electronic Commerce Research and Applications, 13(6), 409-422. doi:https://doi.org/10.1016/j.elerap.2014.08.002

Goulding, J., Nadim, W., Petridis, P., & Alshawi, M. (2012). Construction industry offsite production: A virtual reality interactive training environment prototype. Advanced Engineering Informatics, 26(1), 103-116. doi:https://doi.org/10.1016/j.aei.2011.09.004

Hackl, C., & Wolfe, S. G. (2017). Marketing New Realities: An Introduction to Virtual Reality and Augmented Reality Marketing, Branding, and Communications: Meraki Press.

Haller, K. (2017). 14 - Colour in interior design. In J. Best (Ed.), Colour Design (Second Edition) (pp. 317-348): Woodhead Publishing.

Heidari, M., Allameh, E., de Vries, B., Timmermans, H., Jessurun, J., & Mozaffar, F. (2014). Smart-BIM virtual prototype implementation. Automation in Construction, 39, 134-144. doi:https://doi.org/10.1016/j.autcon.2013.07.004

Jarald, J. (2014). The VR Book Human-Centered Design for Virtual Reality.

Kandaurova, M., & Lee, S. H. (2018). The effects of Virtual Reality (VR) on charitable giving: The role of empathy, guilt, responsibility, and social exclusion. Journal of Business Research. doi:https://doi.org/10.1016/j.jbusres.2018.10.027

Lin, Y., Yu, S., Zheng, P., Qiu, L., Wang, Y., & Xu, X. (2017). VR-based Product Personalization Process for Smart Products. Procedia Manufacturing, 11, 1568-1576. doi:https://doi.org/10.1016/j.promfg.2017.07.297

Paes, D., Arantes, E., & Irizarry, J. (2017). Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems. Automation in Construction, 84, 292-303. doi:https://doi.org/10.1016/j.autcon.2017.09.016

Perroud, B., Régnier, S., Kemeny, A., & Mérienne, F. (2017). Model of realism score for immersive VR systems. Transportation Research Part F: Traffic Psychology and Behaviour. doi:https://doi.org/10.1016/j.trf.2017.08.015

Pour Rahimian, F., Chavdarova, V., Oliver, S., & Chamo, F. (2019). OpenBIM-Tango integrated virtual showroom for offsite manufactured production of self-build housing. Automation in Construction, 102, 1-16. doi:https://doi.org/10.1016/j.autcon.2019.02.009

Rahimian, F. P., & Ibrahim, R. (2011). Impacts of VR 3D sketching on novice designers' spatial cognition in collaborative conceptual architectural design. Design Studies, 32(3), 255-291. doi:https://doi.org/10.1016/j.destud.2010.10.003

Sanchez-Sepulveda, M., Fonseca, D., Franquesa, J., & Redondo, E. (2019). Virtual interactive innovations applied for digital urban transformations. Mixed approach. Future Generation Computer Systems, 91, 371-381. doi:https://doi.org/10.1016/j.future.2018.08.016

Sawczuk, B. (2013). Creating Winning Bids.

Sherman, W. R., & Craig, A. B. (2018). Chapter 9 - Experience Conception and Design: Applying VR to a Problem. In W. R. Sherman & A. B. Craig (Eds.), Understanding Virtual Reality (Second Edition) (pp. 724-779). Boston: Morgan Kaufmann.

Solihin, W., Eastman, C., & Lee, Y.-C. (2017). Multiple representation approach to achieve high-performance spatial queries of 3D BIM data using a relational database. Automation in Construction, 81, 369-388. doi:https://doi.org/10.1016/j.autcon.2017.03.014

Sun, T., Xu, Z., Yuan, J., Liu, C., & Ren, A. (2017). Virtual Experiencing and Pricing of Room Views Based on BIM and Oblique Photogrammetry. Procedia Engineering, 196, 1122-1129. doi:https://doi.org/10.1016/j.proeng.2017.08.071

Wilson, W. (2017). Self-build and custom

build housing (England). House of Commons Library.

Yu, X. (2011). Research and Practice on Application of Virtual Reality Technology in Virtual Estate Exhibition. Procedia Engineering, 15, 1245-1250. doi:https://doi.org/10.1016/j.proeng.2011.08.230

Construction Health and Safety

Perception of the Benefits and Barriers of 4D Modelling for Site Health and Safety Management

Mark Swallow[1*] and Sam Zulu[2]

[1]Leeds College of Building, North Street, Leeds, LS2 7QT.

[2]Leeds Beckett University, School of the Built Environment, Leeds, LS2 8AG

*Email: mswallow@lcb.ac.uk

Abstract

In the UK, construction remains to be a high-risk sector. The dynamic nature of construction is fraught with risk, which can often be difficult to predict and mitigate. The adoption of 4D modelling has been included within the BIM level 2 framework document PAS1192-6:2018, to support the management of health and safety. This paper focuses on the perception of industry professionals in regards to the benefits and barriers of 4D, when used for health and safety management. A focus group comprising of 10 professionals within a selection of industry related sectors were interviewed, and qualitative data collected. The data indicated an 80% awareness of 4D, with 40% of those interviewed currently adopting 4D. However, in most cases the software was not specifically used for health and safety management, although safety risks can be identified in the process. The responses indicated that the key perceived benefits of 4D were in the visualisation and planning of site activities, mainly in the location and movement of plant, working at height and logistics management. Key barriers in the adoption of 4D for health and safety were also identified, including cost, time and a culture within the industry, in which individuals and organisations find it difficult to adapt and except new ways of working.

Keywords: Construction, BIM, 4D modelling, Health and Safety, PAS1192-6:2018

1. Introduction

As digital technologies and processes become further integrated within every day work activates, the way to approach project delivery changes. The construction industry, unlike many others, is a dynamic (Getuli, Giusti, Capone, Sorbi, & Bruttini, 2018; Whitlock, Abanda, Manjia, Pettang, & Nkeng, 2018) and high-risk industry (Li et al., 2018). This high risk could be seen as both commercial risk and also health and safety risk, both areas of which require careful planning and management. The way that information flows through an organisation and a project is key to successful outcomes, ensuring that the correct information is with the correct people, at a sufficient time to enable the most effective decisions to be made. The construction industry is however, known for having complex information flows (Kumar, 2015) and in addition, deep concerns regarding health and safety management (Dawood, Miller, Patacas, & Kassem, 2014; Lacey, 2015). These factors could be traced to the nature of construction, an industry which has previously been criticised for underachieving (Egan, 1998) in addition to this an historic adversarial culture and poor health and safety performance (Egan, 1998; K; Sulankivi, Tauriainen, & Kiviniemi, 2014). Following the release of the government strategy in 2011 and the BIM level 2 mandate in 2016, Bew (2018) believes the industry has progressed, although this is still early stages of its digital transformation. Although the industry has been historically criticised for its lack of innovation (Gledson, 2016) and its adoption of new processes and technologies (Chevin, 2018), the adoption of BIM is shown to be increasing year on year (NBS, 2018) as well as new technologies now being integrated within projects becoming more common place.

The use of innovative technologies can be seen within industry, from modelling software and collaborative common data environments to robotics (Ardiny, Witwicki, & Mondada, 2015; Kuenzel, Teizer, Muller, & Bickle, 2016) and immersive technology (Barnes, 2019; Behzadi, 2016; Yi & Leung, 2019). Although a number of these are still within the testing and feasibility stages of development, 4D modelling has been an area of research, with successful case study applications over recent years.

According to Wang *et al.* (2014), a four-dimensional (4D) model is created by linking the three-dimensional components with the project schedule, this synchronisation of the graphical model components with the schedule data (Dawood et al., 2014; Zhang & Li, 2010) can therefore create a visual construction sequencing models (Gledson, 2016; Hardin & McCool, 2015). These 4D models are used for a number of proposes, including project co-ordination (Gledson, 2016), communication (Azhar & Bahringer, 2013; Ganah & John, 2015; Gledson, 2016; Kassem, Brogden, & Dawood, 2013; Romigh, Kim, & Sattineni, 2017; Kristiina; Sulankivi et al., 2013), logistical planning (Azhar & Bahringer, 2013; Whitlock et al., 2018), and visualisation (Azhar & Bahringer, 2013; Azhar, Behringer, Khalfan, Sattineni, & Maqsood, 2012; Swallow & Zulu, 2019).

As the construction industry continues to develop its adoption of building information modelling (BIM) level 2 processes and digital software, the BSI published PAS1192-6:2018, a BIM level 2 framework document focusing on collaborative sharing and use of health and safety information using BIM. Mordue and Finch (2014) suggests that BIM has been recognised and acknowledged by the HSE, suggesting that its importance is been further elevated, as a way to truly drive health and safety management. PAS1192-6:2018 indicates a clear push for the adoption of modelling software in design development and to improve health and safety (BSI, 2018), stating

> *Each participant shall adopt the use of 3D or 4D construction sequencing model(s) to the support the development and visualisation of safe methods of access and working* (BSI, 2018, p. 11).

The inclusion of 4D modelling within the PAS1192-6:2018 documentation demonstrates its acceptance within the field of information management, project delivery and health and safety. However, with the historically poor adoption of new processes and technology being an identified issue within the industry, how ready is the industry to adopt 4D modelling as standard practice for health and safety management? This paper therefore, is to document industry perceptions of 4D modelling as a tool to manage health and safety, focusing on its perceived impact, benefits and barriers within the construction industry.

2. Materials and Methods

2.1 Background of Health and Safety in the Construction Industry

The very nature of construction often poses pressure on the project team to deliver complex assets on time, to budget and without risk to health and safety. Even with simple projects, the logistics, co-ordination and quality of plant, materials and labour often pose high risk to operatives and those accessing in around the site. For this reason, a high level of health and safety management is required to manage this risk, often involving proactive control measures, which can be costly and timely to plan and execute. Phoya (2017) highlighted that although various control measures are often in place, operatives are still often exposed to risk when carrying out site activities, this is reflected by the 38 fatal injuries reported to the HSE in 2017/2018 (HSE, 2018a). A total of 2.4 million lost working days were recorded each year between 2015/16 and 2017/18 and although non-fatal injuries are on a downward trend, 50,000 are reported each year (HSE, 2018a). With these statistics, the construction industry remains to be one of the highest risk industries in the UK.

The industry is familiar with its historically poor reputation; many infamous reports have highlighted the industries shortcomings including Latham (1994), Egan (1998) and Farmer (2016). Although there has been significant improvement in health and safety and industry image, there are still further improvements to be made. The importance of company culture and personal behaviours towards health and safety has been an area of research for many years. Many methods have been used to improve this factor and in turn, aim to reduce fatality and accident statistics, although is it often these factors which are most difficult to change (Swallow & Zulu, 2019). With key legislation enforced on the industry (such as the Construction Design and Management Regulations 2015) and ethnises on training and education within the sector, further improvements in safety are a clear focus.

Project health and safety management requires planning and co-ordination of the construction team as well as understanding of the project in a holistic view. This could be a wide scope, and should include a clear understanding of the project deliverables, methodology, logistical issues and the specific personal factors of those involved with the activities. As construction projects are dynamic and assets often bespoke, this is a task, which requires precise planning and clear communication (Azhar et al., 2012). This communication is often hindered by poor information creation and exchange, adopting 'traditional' methods, resulting in miscommunication of project outputs, in particular health and safety requirements.

2.2 Benefits and Barriers of 4D Modelling for Construction Health and Safety Management

Zhang et al. (2011) suggests that planning is a fundamental step in managing health and safety in the construction industry. Traditionally, project planning and scheduling would be carried out as an isolated task from the design and modelling aspects, typically in the form of a Gantt chart. Linking the 3D project with the construction schedule can allow the construction process to be graphically visualised and simulated (Ganah & John, 2015). According to Zhou (2009) collaborative 4D should take into account the needs of various members of the project team in order to produce a robust plan, this in turn requires those creating such documents to have knowledge and experience of the construction process.

The key benefits and barriers of BIM and 4D modelling in regards to health and safety management has been an active area for research over recent years and although the culture of the industry cannot be altered by technology alone (Rowlinson, Collins, Tuuli, & Jia, 2010), the collaborative processes, changes of culture and behaviour could be effected by the adoption of use technology. Azhar & Bahringer (2013) recommend the utilization of BIM technologies in improving occupational safety, this can be achieved by allowing designers and constructors to visualise and assess project specific environments and conditions, in turn identify potential hazards. The use of digital technology, including the creation of models and simulations can further influence the ability of the project team to communicate and implement the desired work activities safety (HSE, 2018b). This view is echoed by Azhar et al. (2012) who highlights the benefits of BIM technology, in improving safety by clear collaboration and communications of project situations, linking accurate planning within detailed visualisation of proposed construction methodologies. Mahalingam et al. (2010) concur, identifying 4D as clear benefits including increased stakeholder collaboration, having further visualisation for design and constructability methods as well as being able to identify clashes within the construction process.

Whitlock et al. (2018) also described the benefits of 4D modelling, however mainly in regards to its impact on logistics management. The use of 4D modelling offers a clearer understanding and visualisation of the site layout, and allows for simulations of the construction sequences to be produced during the pre-construction stages allowing for analysis of the proposed schedule. As construction sites are dynamic, the importance of co-ordinating site activates is key. The understanding and communication of temporary site works, which facilitates the construction processes, could also be included within the 4D model. This process offers clearer co-ordination of site plant, fencing and pedestrian walkways. As opposed to a using 2D information which can be often misinterpreted or difficult to communicate, a 4D environment can provide clearer understanding amongst all of the project team of the proposed site plans and methodology. This in turn can allow for more precise logistics management, increasing the ability to foresee hazards, optimise locations of temporary works, reduce time / space clashes and to minimise health and safety risk.

Sidani et al. (2018) concluded that BIM processes and 4D modelling software can be effective in improving health and safety within the construction industry. Prevention planning methods, such as the use of 4D for visualisation of site actives in order to access potential schedule conflicts, identifying optimised sequences and to identify safety risks both during design and construction stages can be key benefits. In addition, safety training and accident investigation data can also be advantages of such methods. In an empirical study, Swallow & Zulu (2019) collected and analysed quantitative data to identify adoption and perceptions of 4D when used as a safety management tool, in light of the publication of PAS1192-6:2018. Findings indicated a 35% adoption of 4D within the construction sector and concluded that the primary purpose for its use was not in health and safety management. Key benefits being in the adding of value through visualisation and clearer communication of project outputs and scheduling co-ordination, which in turn can have a positive impact on safety. Whilst barriers included culture, resistance to change, costs and time to implement the processes and software, Kassem et al. (2013) also added by concluding that barriers include a lack of experience, universal use and contract type.

Whitlock et al. (2018) identified barriers to the adoption of 4D, with limited involvement of the supply chain and minimum levels of site training in 4D software being present. The accuracy of the 4D model once works commences was also an aspect in which could cause barriers to its use, due to the dynamic nature of construction it was highlighted that although the models where useful in identify hazards and optimising sequencing, the same processes are not necessarily utilised on site, Whitlock et al. (2018) stated

> *4D BIM logistics models produced at the outset of the project are infrequently utilised to coordinate logistics processes following commencement of the scheduled works, instead reverting back to management of construction logistics via 2D information* (Whitlock et al., 2018, p. 52)

Kassem et al. (2013) suggests barriers to implementation of 4D planning within the industry, highlighting consults limited knowledge of the benefits of 4D being a key aspect, with 34% of surveyed consultants aware of 4D. Other key barriers to the wide spread use of 4D modelling included and lack of understanding of the business value and experience amongst the workforce, in addition to this a resistance to change in working methods and software adoption in addition to the additional up front cost and time factors. Romigh et al. (2017) concluded that 4D has potential within the industry to allow clear visualisation of work processes and allows the creation of virtual alternatives which can be simulated and communicated effectively. The key issues identified being in the “cumbersome nature of the software” in addition to the training and learning curves required to operate such systems.

3. Methodology

Further to the publication of PAS1192-6:2016, promoting and advocating the use of this software to improve safety in construction, the paper sets out to investigate current perception of BIM and 4D modelling with specific regards to its uses, impact, benefits and barriers for health and safety management. A qualitative study approach was adopted and data was collected through interviews with construction industry professionals. Such an approach was deemed appropriate as the study sort to draw on the experiences and perceptions (O.Nyumba, Wilson, Derrick, & Mukherjee, 2018) of the participants who were chosen using selective sampling technique. Structured interviews, enabled the collection of data in a consistent format which could also be further explored (Farrell, 2011; Naoum, 2013), using a combination of open and closed questions. This gave the participants the opportunity to expand the response from their experience and understanding, careful considerations were given to reduce prompting of responses (Bryman & Bell, 2007). The industry professionals were selected through selective sampling (Naoum, 2013) and ranged from national contractors and designers to local contractors and subcontractors, ensuring that varied sectors were chosen to show a fair overview.

4. Results

4.1 Sample Demography

Ten interviews were conducted in order to collect qualitative data, the interviewees comprised of a selection of the industry sector professionals each holding management positions, as indicated in table 1 and 2. The data shows interviewees being within construction, civil, building services and manufacturing linked with the construction sector.

Table 1 Sample Demography (summary)

Interviewee	Position	Industry	Experience	BIM use
1	BIM manager	Building services engineering	Quantity surveying, BIM information management.	Experience on BIM level 2 projects
2	Contracts manager	Construction	Site management of complex projects, logistics management and H&S	No experience of BIM level 2 projects
3	Company director	Manufacture	Quantity surveying, risk management and procurement strategies. Senior management experience.	Experience of BIM level 2 projects
4	Company director	Manufacture	Site operations and management, product manufacturing risk management and procurement strategies. Senior management experience.	No experience of BIM level 2 projects
5	Company director	Construction	Site operations, logistics, H&S and co-ordination management. Experience in procurement and risk management.	No experience of BIM level 2 projects
6	Logistics manager	Manufacture	Site operations within construction and manufacturing. Logistics, planning and H&S management. Training and educational experience.	No experience of BIM level 2 projects

7	Senior digital manager	Civil infrastructure	Site operations and senior BIM information management. Digital technology and BIM process integration experience	Experience on BIM level 2 projects
8	Site manager	Construction	Site management of complex projects, logistics management and H&S	Experience on BIM level 2 projects
9	Product designer	Manufacture	Digital design and manufacturing. Experience in procurement and quantity surveying	No experience of BIM level 2 projects
10	Project manager	Construction	Site management of complex projects, logistics management and H&S. experience in site technologies and BIM processes	Experience on BIM level 2 projects

Table 2 Sample Demography (sector)

Industry Sector	**Interviewee**	**Total number of interviewees**	**Percentage**
Construction	2, 5, 8, 10	4	40%
Civil infrastructure	7	1	10%
Building services engineering	1	1	10%
Manufacture	3, 4, 6, 9	4	40%
Total		10	100%

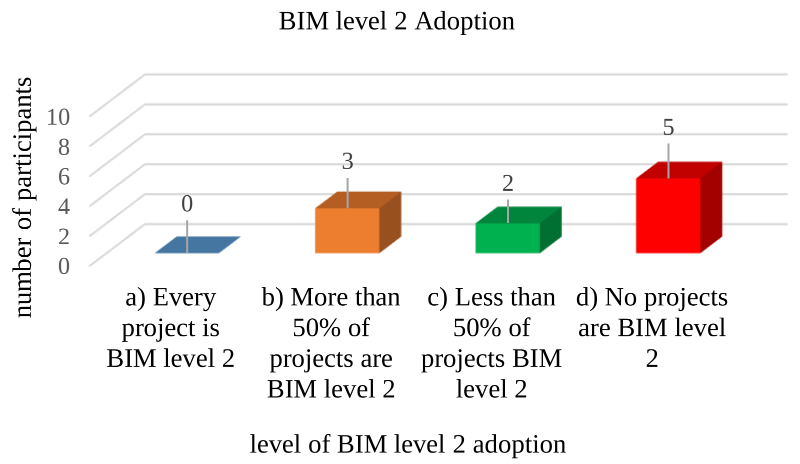
The interviews recorded the company size in which the interviewees were employed; the total employees ranged from 40 to 1000+ employees in a number of companies. This range was important in order to achieve a fair overview, as smaller scale companies may have different needs or perceptions to larger ones. Table 3 illustrates the company sizes, it can be seen that the majority (40%) of interviewees where employed by companies who employ over 1000 people although the spread is not grossly impropriate.

Table 3 Company Sizes (by employee number)

Number of employees within company	**Interviewee**	**Total number of interviewees**	**Percentage**
less 50 employees	4, 5, 9	3	30%
between 50 - 200 employees	2	1	10%
between 200 - 1000 employees	3, 8	2	20%
more than 1000 employees	1, 6, 7, 10	4	40%
Total		10	100%

4.2 BIM level 2 Adoption

The adoption of BIM level 2 is key to this study as the PAS1192-6:2018 document is a framework for this level of maturity. Participants where asked during the interviews to state their companies adoption of BIM level 2. The data, indicated in figure 1 shows an even division, 50% of those interviewed are working on BIM level 2 projects and that 50% are not, the adoption of BIM level 2 on every project was not confirmed by the interviewees.



BIM level 2 Adoption	**Interviewee**	**Number of Participants Agreed**	**Percentage**
Every project is BIM level 2		0	0%
More than 50% of projects are BIM level 2	1, 7, 10	3	30%
Less than 50% of projects BIM level 2	3, 8	2	20%
No projects are BIM level 2	2, 4, 5, 6, 9	5	50%
Total		10	100%

Figure 1 BIM level 2 Adoption

4.3 4D Modelling Awareness and Adoption

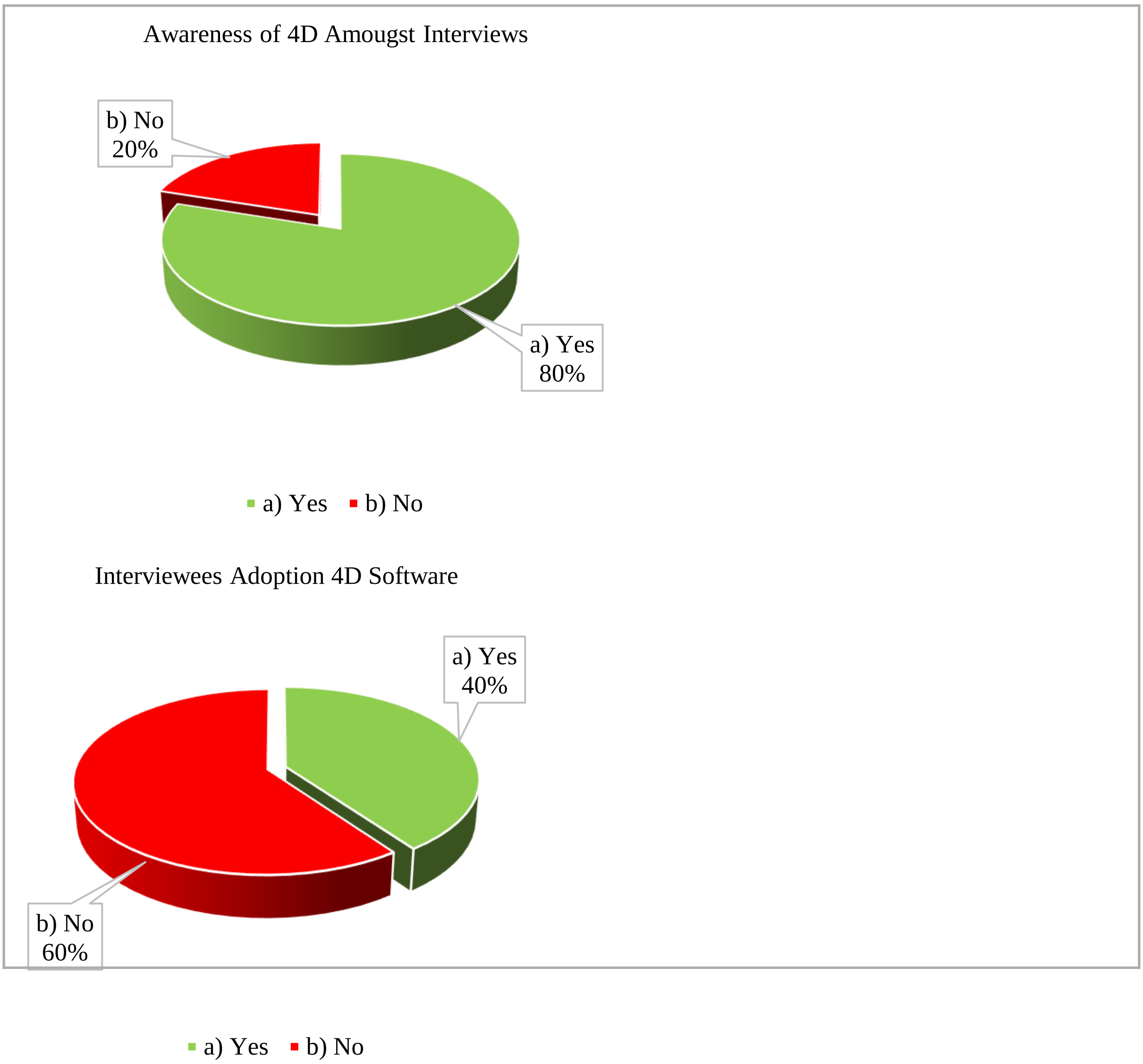
The awareness and adoption of 4D was documented for this study, figure 2 shows the total in both of these areas. The interviewee's responses indicated a high percentage of awareness of 4D at 80%, with total adoption 40% of those interviewed currently adopting 4D. The data also showed that of the interviewees who were employed by companies not working on a BIM level 2 project, 100% were aware of 4D. The interviewees who confirmed the adoption of 4D were ask to identify the software used, the software identified were Navisworks and Synchro pro. The interviewees who used the software gave additional statements in the interviews; most cases the 4D software for a number of reasons, not specifically for health and safety management.

The interviewees were asked *"if you are adopting 4D on your projects, does the software assist in the management of onsite health and safety? If so how?"*

The response to this interview question varied, although many responded stated that 4D was used for visualisation and logistics planning as apposed to a specific health and safety tool.

Interviewee 7: "*yes it does, information can passed between the project team to make informed decisions. Plans are made with a 6 week look ahead, often due to the changes on site. Projects used to be 2D and used to not take many factors into account. We are now in a 3D world, in tight sites this 4D very useful for difficult logistical planning; 4D is confirmation that you are doing things properly*"

Interviewee 9: "*It does, however health and safety is not the full the concern, 4D is more of a management tool and for visualisation"*



Interviewee	Aware of 4D	Adopting 4D
1	yes	yes
2	yes	no
3	no	no
4	yes	no
5	yes	no
6	yes	no
7	yes	yes
8	no	no
9	yes	yes
10	yes	yes

Figure 2 4D Interviewee Awareness and Adoption of 4D

4.4 Benefits to 4D Adoption for Health and Safety Management

During the structured interviews, open questions were asked, *"in regards to using 4D for health and safety management, what would you suggest are the key benefits?"* their responses were recorded and the key benefits identified from each interviewee. The data in figure 4 shows that many of the participants identified similar benefits, with perception of the benefits in the planning for site plant and vehicle movement in addition to clearer visualisation being the highest ranked.

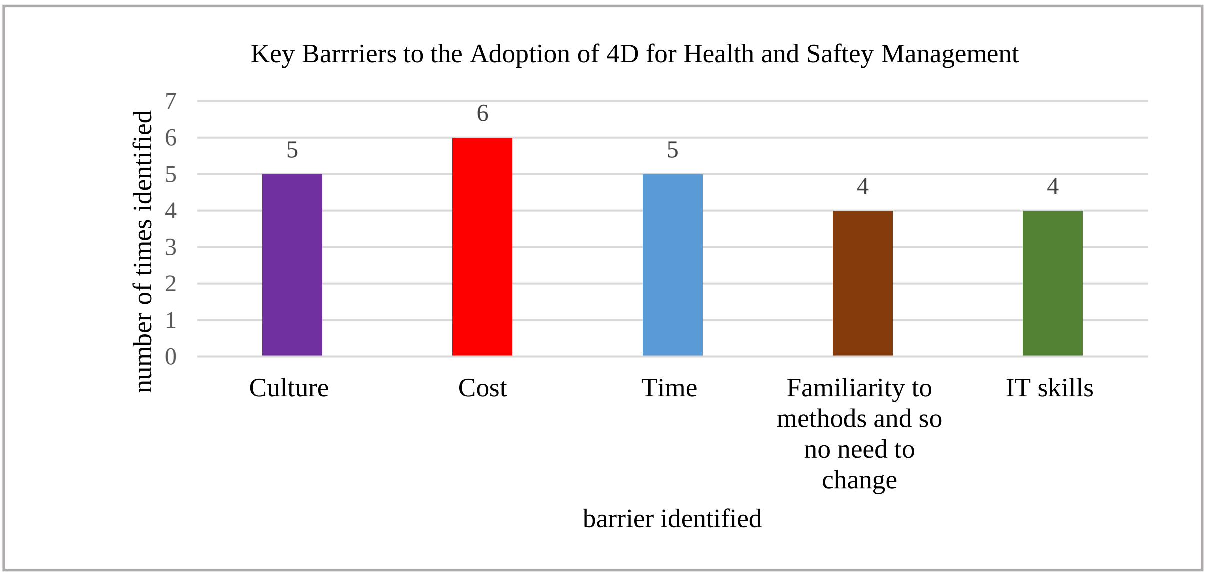
Table 4 Key Benefits to the Adoption of 4D for Health and Safety

Key Benefits to 4D Adoption for Safety Management	**Interviewee**	**Total Number of Participants Highlighted During Interviews (out of 10)**
Planning for plant location and movement	1, 2, 4, 5, 6, 7, 8, 9, 10	9
For operatives to visualise the environment	1, 2, 3, 5, 6, 7, 8, 10	8
Planning working at height	2, 3, 5, 6, 7, 8, 10	7
Planning site logistics	1, 3, 5, 6, 8	5
Planning pedestrian walkways and segregation	3, 4, 6, 9, 10	5
Planning for working in confined spaces	2, 5, 6, 9	4
Planning manual handling	4, 9	2
Planning for welfare locations	8	1

4.5 Barriers to 4D Adoption for Health and Safety Management

The interview participants were asked *"Would you say there are any barriers to using 4D modelling for safety management on site? If so what would these barriers be?"* As figure 3 indicates, a number of barriers to the use of 4D were identified, these factors also corresponded to those identified in key literature sources. The most common barriers identified being in the costs and time to implement 4D on site, inn addition a resistant culture and many unwilling to change familiar processes.

Figure 3 Interviewee Perception of the Benefits of 4D Modelling for Safety Management



key Barriers to 4D adoption Identified	Interviewee	Number Participants Highlighted (out of 10)
Culture	1, 3, 7, 8, 9	5
Cost to implement	1, 2, 4, 5, 8, 10	6
Time to implement	1, 2, 3, 4, 8	5
Familiarity to methods and so no need to change	1, 5, 9, 10	4
Lack of IT skills	4, 5, 6, 10	4

Example statements taken from the industry interviews included:

> **Interviewee 4:** *"Does the increase in time and cost in doing these 3D, 4D models really add value to the project. In theory the principal sounds good however in reality does the savings warrant the time and cost to implement?"*
>
> **Interviewee 5:** *"The software would need to be easy to operate and require minimal training without the need for extra staff. The software needs to be fast and adaptable"*
>
> **Interviewee 7:** *"There is a resistance to move people on to a new way of working".*
>
> **Interviewee 8:** *"Resources and training would be a barrier, the training would take time and resources cost money"*
>
> **Interviewee 9:** *"People fear of the new and fear of innovation"*

4.6 Influence PAS 1192-6:2018 on 4D Adoption

To conclude the interviews, the participants were asked "*Would you agree that the inclusion of 4D modelling for safety management within PAS1192-6:2018 will influence the adoption of 4D within the industry?"* Table 5 identifies the responses, with 80% agreeing that these standards will have a positive impact on the adoption of 4D for health and safety.

Table 5 Perception of PAS1192-6:2018 Having Influence on 4D Adoption

Perception of PAS1192-6:2018 in Regards to Influence on 4D adoption	Interviewee	Total (out of 10)
Yes	1, 2, 3, 6, 7, 8, 9, 10	8
No	4, 5	2

During this discussion with the interviewees, one participant noted

Interviewee 4: *4D would be useful and would help identify health and safety risks on a construction site but until the use of this becomes law, it will only be the larger company who adopt it.*

5. Discussion and Conclusion

The industry interviews confirmed a number of key aspects in regards to awareness, adoption, benefits and barriers of 4D within the construction industry. The findings indicated a high awareness of 4D amongst participants, with interviews highlighting that although 4D is used, the software is not used exclusively for health and safety. The use of 4D can have impact on health and safety by highlight hazards thoughts its visualised planning environment. The interviews identified many perceived benefits to the use of 4D for health and safety, including the increased visualisation and planning of site plant, logistics and high risk works such as working at heights. Through rehearsing of site activities and planning the project in a virtual 4D environment, the clearer visual communications can allow the optimum locations and work processes to be selected in terms of time and cost saving and site safety. The process and software allow the project team to identify foreseeable hazards allowing for clear visualisation and communication of hazard elimination and control, including the planning of both temporary works and non-temporary works.

The study validated many barriers to the adoption to 4D as standard practice in the construction industry, with the cost and time to implement alongside a culture, which is resistant to change and adopt new ways of working. The impact of PAS1192-6:2018 in regards to the adoption of 4D could be assessed in time, although the perception of its introduction looks to be positive. The adoption of BIM level 2 in the industry, as well as the awareness and education of these industry standards and benefits could also have an influence on the adoption of 4D. The industry may continue to have a slow adoption of new technologies and processes however, it is clear that in order to reduce risk during the construction stages and reduce industry fatalities, accurate planning is key. 4D allows these often-unforeseen issues to be identified, planned and managed ahead of time; with hazards removed or more effectively controlled, the reduction of risk to operatives can inevitably be achieved.

Ethics Statement

We can confirm that appropriate ethics approval was obtained for this research and that participants to the study were made aware of the purpose and nature of the study. All interview participants were advised of the voluntary nature of their participation and consented using the institution approved documents, following approved procedures.

References

Ardiny, H., Witwicki, S., & Mondada, F. (2015). Are Autonomous Mobile Robots Able to Take Over Construction ? A Review. *International Journal of Robotics*, *4*(3), 10–21.

Azhar, S., & Bahringer, A. (2013). A BIM-based Approach for Communicating and Implementing a Construction Site Safety Plan. *Proceedings of the 49th ASC Annual International Conference*. Associated Schools of Construction.

Azhar, S., Behringer, A., Khalfan, M., Sattineni, A., & Maqsood, T. (2012). BIM for Facilitating Construction Safety Planning and Management at Jobsite. *Proceeding of the CIB W099 International Conference on "Modelling and Building Health and Safety,"* 82–92. Retrieved from https://www.irbnet.de/daten/iconda/CIB_DC25800.pdf

Barnes, P. (2019). *BIM in Principle and Practice* (3rd Ed). London: ICE.

Behzadi, A. (2016). Using Augmented and Virtual Reality Technology in the Construction Industry. *American Journal of Engineering Research*, *5*(12 January), 350–353. Retrieved from https://pdfs.semanticscholar.org/2fc8/2c3dfd09f7439fa75a6015c5a8eea1ff19fc.pdf

Bew, M. (2018). Prelims. *Construction Manager*. Retrieved from http://www.bimplus.co.uk/news/lowest-cost-culture-blocking-bim-level-2-adoption-/

Bryman, A., & Bell, E. (2007). *Business Research Methods* (3rd Ed). New York: Oxford.

BSI. (2018). *PAS1192-6:2018 specification for the collaborative sharing and use of structured Health and Safety information using BIM*. London: BSI.

Chevin, D. (2018, April). BIM Level 2 Uptake Still Slow but AR and Automation Up. *Construction Manager Insight on BIM*, 22–24.

Dawood, N., Miller, G., Patacas, J., & Kassem, M. (2014). Construction Health and Safety Training: the Utilisation of 4D Enabled Serious Games. *Journal of Information Technology in Construction (ITcon)*, *19*(19), 326–335. Retrieved from http://www.itcon.org/2014/19

Egan, S. J. (1998). *Rethinking Construction the Report of the Construction*. Norwich.

Farmer, M. (2016). *The Farmer Review of the UK Construction Labour Model*. Construction Leadership Council.

Farrell, P. (2011). *Writing a built environment dissertation practical guidance and examples*. Sussex: Wiley Blackwell.

Ganah, A., & John, G. A. (2015). Integrating building information modeling and health and safety for onsite construction. *Safety and Health at Work*, *6*(1), 39–45. https://doi.org/10.1016/j.shaw.2014.10.002

Getuli, V., Giusti, T., Capone, P., Sorbi, T., & Bruttini, A. (2018). A Project Framework to Introduce Virtual Reality in Construction Health and Safety. *AlmaDL Journals, New Frontiers of Construction Management Workshop*, *09*(13), 166–175. Retrieved from https://in_bo.unibo.it/article/view/8830/8950

Gledson, B. (2016). Exporing the consequences of 4D BIM innovation adoption. *Proceedings of the 32nd Annual ARCOM Conference*, *1*(September), 73–82.

Hardin, B., & McCool, D. (2015). *BIM and Construction Management Proven Tools, Methods and Workflows* (2nd Editio). Indiana: Indiana: Wiley.

HSE. (2018a). *Construction statistics in Great Britain, 2018*. Retrieved from http://www.hse.gov.uk/statistics/industry/construction.pdf

HSE. (2018b). Improving Health and Safety Outcomes in Construction. Making the Case of Builing Information Modelling (BIM. *Health and Safety Executive*, *RR 235*. Retrieved from http://www.hse.gov.uk/research/rrpdf/rr235.pdf

Kassem, M., Brogden, T., & Dawood, N. (2013). BIM and 4D planning: a holistic study of the barriers and drivers to widespread adoption. *Journal of Construction Engineering and Project Management*, *2*(4), 1–10. https://doi.org/10.6106/jcepm.2012.2.4.001

Kuenzel, R., Teizer, J., Muller, M., & Bickle, A. (2016). SmartSite: Intelligent and Autonomous environments, machinery and porcesses to realize smart road construction projects. *Automation in Construction*, *71*(1), 22–33.

Kumar, B. (2015). *A Practical Guide to Adopting BIM in Construction Projects.* Scotland: Whittles Publishing.

Lacey, J. (2015). *The Management of Construction Health and Safety Risk* (Fourth Edi). Stourbridge: rms.

Latham, M. (1994). *Constructing the team*. London: HMSO.

Li, X., Yi, W., Chi, H., Wang, X., & Chan, A. (2018). A critical review of virtual and augmented reality (VR/AR) applications in construction safety. *Automation in Construction*, *86*, 150–162. Retrieved from https://www.sciencedirect.com/science/article/pii/S0926580517309962

Mahalingam, A., Kashyap, R., & Mahajan, C. (2010). An evaluation of the applicability of 4D CAD on construction projects. *Automation in Construction*, *19*(2 March), 148–159. Retrieved from https://www.sciencedirect.com/science/article/pii/S092658050900185X

Mordue, S., & Finch, R. (2014). *BIM for Construction health and Safety*. Newcastle: RIBA.

Naoum, S. . (2013). *Dissertation research and writing for construction students* (3rd Editio). New York: Routledge.

NBS. (2018). *National BIM Report*. Newcastle upon tyne: NBS.

O.Nyumba, T., Wilson, K., Derrick, C. J., & Mukherjee, N. (2018). The use of focus group discussion methodology: Insights from two decades of application in conservation. *Methods in Ecology and Evolution*, *9*(1), 20–32. https://doi.org/10.1111/2041-210X.12860

Phoya, S. (2017). The Practice of Communication of Health and Safety Risk Information at Construction Sites in Tanzania. *Journal of Engineering Trends and Technology*, *47*(7 May), 385–393.

Romigh, A., Kim, K., & Sattineni, A. (2017). 4D Scheduling: A Visualization Tool for Construction Field Operations. *53rd Associated Schools of Construction Annual International Conference Proceedings*, 395–404. Retrieved from http://ascpro0.ascweb.org/archives/cd/2017/paper/CPRT130002017.pdf

Rowlinson, S., Collins, R., Tuuli, M. M., & Jia, Y. (2010). Implementation of Building Information Modeling (BIM) in construction: A comparative case study. *AIP Conference Proceedings*, *1233*(1), 572–577. https://doi.org/10.1063/1.3452236

Sidani, A., Duarte, J., Baptista, J. S., Martins, J. P., & Soeiro, A. (2018). Improving construction safety using BIM-Based sensor technologies. *2º Congresso Português de Building Information Modelling*, (1), 161–169.

Sulankivi, K;, Tauriainen, M., & Kiviniemi, M. (2014). Safety Aspect in Constructability Analysis with BIM. *Proceedimgs of CIB W099 Achieving Sustainable Construction Health and Safety*, 586–596. Retrieved from https://www.researchgate.net/profile/Hamza_Gabriel/publication/275037120_Investigation_of_fall_protection_practices_in_the_construction_industry_of_Pakistan/links/554310940cf234bdb21a309a.pdf#page=599

Sulankivi, Kristiina;, Zhang, S., Teizer, J., Charles, M., Kiviniemi, M., Romo, I., & Granholm, L. (2013). Utilization of BIM-based Automated Safety Checking in Construction Planning. *CIB World Building Conference*, (May), 11. Retrieved from https://www.researchgate.net/publication/236885338_Utilization_of_BIM-based_Automated_Safety_Checking_in_Construction_Planning

Swallow, M., & Zulu, S. (2019). Benefits and Barriers to the Adoption of 4D Modeling for Site Health and Safety Management. *Frontiers in Built Environment*, *4*(86 January). https://doi.org/10.3389/fbuil.2018.00086

Wang, W. C., Weng, S. W., Wang, S. H., & Chen, C. Y. (2014). Integrating building information models with construction process simulations for project scheduling support. *Automation in Construction*, *37*(January), 68–80. https://doi.org/10.1016/j.autcon.2013.10.009

Whitlock, K., Abanda, F. H., Manjia, M. B., Pettang, C., & Nkeng, G. E. (2018). BIM for Construction Site Logistics Management. *Journal of Engineering, Project, and Production Management*, *8*(1), 47–55.

Yi, R., & Leung, T. (2019). Leading Safety Indicators and Automated Tools in the Construction Industry. *Proceedings of 34th International Symposium on Automation and Robotics in Construction (ISARC 2017) Leading*, (September 2018). https://doi.org/10.22260/ISARC2017/0106

Zhang, J., & Li, D. (2010). Research on 4D virtual construction and dynamic management system based on BIM. *Proceedings of the International Conference on Computing in Civil and Building Engineering*. Retrieved from http://www.engineering.nottingham.ac.uk/icccbe/proceedings/pdf/pf78.pdf

Zhang, S., Lee, J., Venugopal, M., Teizer, J., & Eastman, C. (2011). Integrating BIM and Safety: An Automated Rule-Based Checking System for Safety Planning and Simulation. *CIB W99*

Conference, 1–13. Retrieved from http://www.irbnet.de/daten/iconda/CIB_DC24442.pdf

Zhou, W. (2009). An Investigation into a Distributed Virtual Reality Environment for Real-Time Collaborative 4D Construction Planning and Simulation. PhD Thesis (University of Wolverhampton). Retrieved from http://wlv.openrepository.com/wlv/handle/2436/98506

A semantic model for computer vision-based hazard identification in construction

Weili Fang[1], Hanbin Luo[1*] and Peter E.D. Love[2]
[1] Dept. of Construction Management, School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, 430074, Hubei, China
[2] Dept. of Civil Engineering, Curtin University, Perth, Western Australia, Australia
* email: luohbcem@hust.edu.cn

Abstract

Potential hazards for people working on construction sites include falls from heights (FFH), the collapse of trenches and scaffolding, electric shocks and failure to use proper personal protective equipment. Such hazards are major contributors to accidents and fatalities. To assist with the mitigation of accidents and fatalities, computer vision has been used to automatically detect safety hazards. Yet as the definition of safety violation becomes more complicated, interdependent and stringent, there is a likelihood that prevailing computer vision approaches will be unable to detect emerging hazards, which would render them to be obsolete unless they can accommodate change and the nuances of construction. To address this problem, this paper combines computer vision algorithms with ontology to develop a novel and robust semantic approach that is able to automatically and accurately recognize hazards. Our proposed semantic computer vision approach consists of (1) an ontological model for safety hazards; (2) detection of object entities and their attributes; (3) extraction of spatial relationships from images, and (4) reasoning data for hazard identification with a graph database. This paper uses the detection of FFH hazards as an example to illustrate the proposed approach. The research demonstrates that the proposed approach can successfully detect FFH hazards in a variety of contexts from images.

Keywords: Computer vision, hazard identification, ontology, safety

1. Introduction

According to the Occupation Safety and Health Administration (OSHA), for example, the construction industry is responsible for more than 20% of worker fatalities in the United States [1]. In the United Kingdom, for example, a similar scenario occurs where construction accounts for the greatest number of fatalities across all sectors [2]. The industry is having to work with less experienced people with equipment in high demand, which generates fresh hazards in a business that is inherently risky.

To address this problem, hazard analysis is typically undertaken prior to construction, which may be performed using manual methods and/or three-dimensional (3D) models [3-4]. Yet hazards can change once construction commences and their identification then needs to be undertaken manually, which can be a labour-intensive and time-consuming process. To overcome the drawbacks of manually identifying hazards, computer vision-based approaches have been developed (e.g., [5-10]). For example, Fang et al. (2018a) [8] proposed a combination of Faster R-CNN and a classification network to identify workers when they were not wearing their safety harness while working at heights. Similarly, Fang et al. (2019) [10] developed a computer vision approach with Mask R-CNN to identify worker traversing on structural supports. Usually, one computer vision algorithm is used to identify a single safety hazard in a scene. For example, computer vision has been widely used to determine if an individual is wearing their safety helmet. Realistically, however, a safety hazard involves a combination of conditions. Therefore, there is a need to move away from using a single computer vision algorithm to a position where a number of safety hazards can be simultaneously detected.

To address this problem, a novel approach that combines computer vision and ontology to automatically detect safety hazards is proposed. The goal of our research is to determine whether hazards with complex rules can be identified using our proposed semantic vision-based approach. Ontology is used to enable computer applications to easily represent and reason safety knowledge, and with computer vision being used to automatically detect objects and extract attributes from images (i.e., classes and distance). The paper commences by providing a review of computer vision-based object detection approaches and applications of ontology-based risk management that have been developed in construction.

2. Related Work

2.1 Computer Vision-based Object Detection

Computer vision has been utilized to undertake a number of tasks in construction such as productivity analysis [11], progress monitoring [12], and the recognition of unsafe behaviour [8-10]. Vision-based identification of different objects is an innate feature of vision-based applications. Vision-based object detection within the domain of construction has focused on utilizing the following approaches: (1) handcrafted features; and (2) deep learning.

Handcrafted feature-based methods tend to employ a two-stage procedure. Firstly, features from images and videos are extracted by descriptors such as Histogram of Oriented Gradients (HOG) [13] or Histogram of Optical Flow (HOF) [14]. Secondly, these extracted features are put into a classifier such as Support Vector Machine (SVM). For example, Memarzadeh (2012) [15] combined a HOG and color features with a new multiple binary SVM classifier to automatically detect and distinguish between a person and equipment using videos. Despite the success of hand-crafted feature-based approaches they are manually created and therefore there is a trade-off between detection accuracy and computational efficiency (i.e., speed) arises.

Deep learning has provided the ability to automatically extract and learn features in an end-to-end manner from images with higher levels of accuracy [16]. Several studies have demonstrated the potential of CNN's for object detection and action recognition on construction sites [9, 17-18]. For example, Fang et al. (2018b) [9] developed an improved Faster R-CNN to identify objects from images and have achieved an accuracy with 91% and 95% when detecting individuals and excavators, respectively.

A review of computer vision-based studies in construction reveals that they have achieved acceptable levels of accuracy (i.e., precision, recall) on object detection and attributes (e.g. distance). For example, Kim et al. (2017) [19] applied a transformation matrix to determine the distance between objects from a single image. Drawing on the work of Kim et al. (2017) [19] and the research of Fang et al. (2018b) [9] an improved Faster R-CNN is selected as an approach to detect objects from two-dimensional (2D) images, and a transformation matrix [19] is used to compute the distance of objects from a single image.

2.2. Ontology-based Risk Knowledge Management

Ontology is a formal conceptualization of knowledge, which is a simplified view of a domain that describes objects, concepts, and relationships between them. Semantic Web technology, for example, can allow various sources of information to be made available in a format that can be searched and retrieved from the Internet [20]. Thus, the combination of semantic web technology with ontology can enable lots of advantages to be realized, such as, knowledge extending or changing. [20-22]. Ontologies-based approaches have been extensively applied to numerous aspects of construction, such as energy management [23-24], and risk management [25]. For example, Zhou *et al*. (2016) [25] reviewed ontology-based research to identify gaps in knowledge within the extant literature.

The aforementioned studies demonstrate the potential of ontology technology in supporting risk management, especially as it can be used to raise the level of safety awareness. By organizing knowledge as a logical semantic expression, it can be shared using ontology technologies and therefore enable semantic interoperability. As a result, the structured and unified knowledge in the ontology can be understood and readily operated by different parties and computer applications and thus enable the re-use of knowledge to be promoted. However, to the best of our knowledge, there has been no research that has combined computer vision and ontology to identify hazards on construction sites.

3. Research Approach

Our proposed semantic computer vision-based approach comprises four procedures: (1) ontological model for construction hazards; (2) computer vision-based entity and attributes detection; (3) extraction of spatial-relationship from images; and (4) reasoning data for hazard identification with a customized graph database. Figure 1 presents the workflow of our proposed hybrid semantic computer vision-based approach, which integrates computer vision and ontology. The procedure to implement our approach is described in the following steps that are described in further detail in the sections hereinafter.

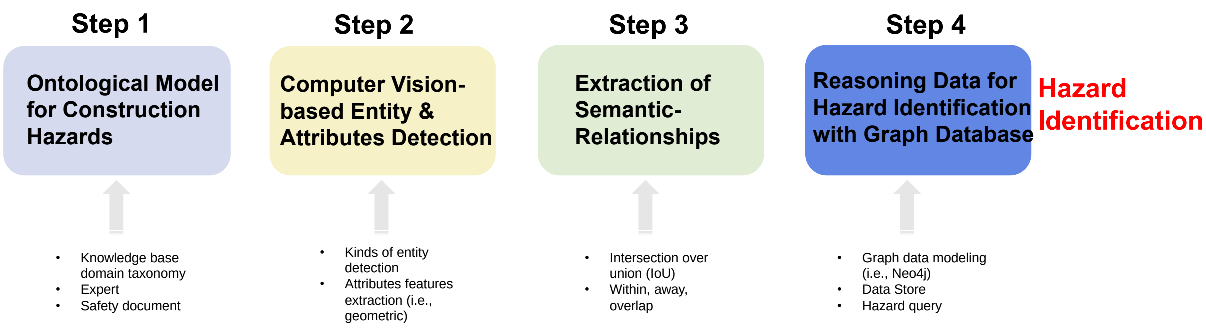


Fig. 1. Workflow of proposed hybrid semantic computer vision approach

Step 1: Ontological Model for Hazards

The initial process for implementing our semantic computer vision-based hazard identification model was to develop a taxonomy of hazards. The Chinese code for 'Quality and Safety Inspection Guide of Urban Rail Transit Engineering', for example, was selected as a point of reference to examine hazards for a metro-rail project that is being constructed in Wuhan, China.

Based on the taxonomies, the 'HowNet' structure was further extended, and then applied to the ontological model used for identifying hazards. HowNet is "an on-line common-sense knowledge base, unveiling inter-conceptual relations and inter-attribute relations of concepts as connoting in Chinese and English bilingual lexicons" [26-27]. Within the context of construction, a hazard can be defined by its: given time and space, and the entities (with specific attributes) undergo certain activities [28-29]. Thus, a hazard event consists of semantic information that specifies its: (1) entity; (2) activity; (3) location; (3) time; (4) attribute.

Step 2: Computer Vision-based Entity and Attributes Detection

The goal of our research is to develop a computer vision approach that can be used to early warn construction hazards. With this in mind, we use computer vision to identify contextual information from construction sites, including hazard entities and its attributes. Thus, the following types of information (e.g., classes of entities and their attributes) are extracted to identify hazards by using reasoning modelling.

- Entity Detection

Entities can be divided into four types of objects: (1) people; (2) equipment; (3) materials; and (4) environment. In this research, two types of detection approaches are used: (1) object detection; and (2) scene recognition. Here, an object detection approach is used to detect people, equipment (i.e., excavator), and materials (e.g., structural support). The scene recognition approach, one of the hallmark tasks of computer vision, allowing defining a context for object recognition, is used to detect working at a height and foundation pit. In this research, built on our previous study [9], Faster R-CNN is applied to detect an individual, excavator, and structural support. In addition, a Unified Perceptual Parsing approach (UPP) is used to effectively segment concepts from images that can be used to recognize scenes [30].

- Attributes Extraction

As our research focuses on identifying hazards based on distance and spatial features, we only need to extract two types of attributes: (1) the coordinates of each object in the image; and (2) their distance between objects. We, therefore, utilized the transformation matrix [19] within our hybrid semantic computer vision model to compute distances between objects.

Step 3: Extraction of Spatial-Relationships from Images

After identifying an object's types and their attributes, three spatial relationships between the objects can be computed: (1) within; (2) overlap; and (3) away. An example of a spatial relationship is presented in Figure 2. In this research, the choice of terminology and semantics for the spatial relation is based on the distance between objects (between two geometries a and b) according to the safety rules that were established from the prevailing Chinese codes.

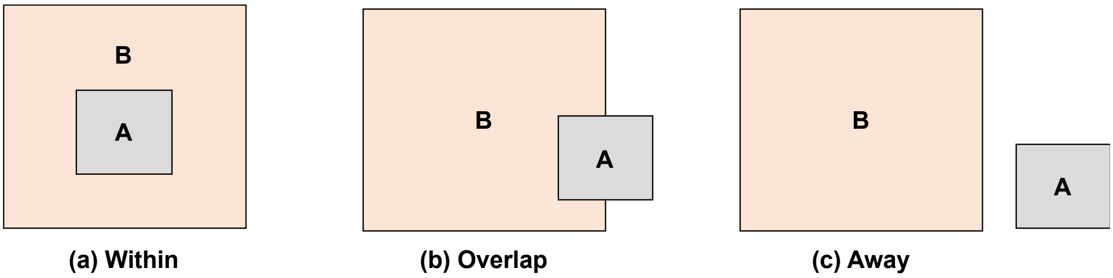


Fig. 2 Examples of spatial relationship

The spatial relationship of object A and object B is defined as the IoU of the bounding box A and bounding box B, as shown in Eq. [1]:

$$IoU(A,B) = \frac{area(A) \cap area(B)}{\min\{area(A), area(B)\}} = \begin{cases} 1 & within \\ [0,1] & overlap \\ 0 & away \end{cases} \quad \text{Eq. [1]}$$

Step 4: Reasoning Data for Hazard Identification Using Graph Database

We use a graph database, Neo4j graph database, to present the safety knowledge for reasoning in a highly accessible way [31-32]. To automatically identify hazards, we perform the following tasks: (1) data modelling; and (2) automated reasoning and query.

- Data Modelling

The procedure to extract objects classes and their spatial relationships have been described above. The outputs from these procedures are saved as a ".CSV" file and loaded in the Neo4j database. The Neo4j database automatically processes the data and then provides an output.

- Automated Reasoning and Query

On completion of the modelling process in the graph database, the final step is to identify the hazards by querying the unsafe behaviour rules that had been defined in the model. The as-built graph database is constructed based on the objects and their spatial relationship, the unsafe rules are derived from the safety codes, which were re-defined as the queries.

4. Case Study

To demonstrate and test the validity of our developed semantic model, we can focus on identifying the unsafe condition that may lead to FFH (Table 2). We have selected an urban subway system under construction in Wuhan China to evaluate the effectiveness of detection for the developed semantic approach.

Table 1. Checklist of unsafe behaviour related to FFH.

Number	**Unsafe behaviour description**
1	There should be no more than two people in a man basket
2	Workers should not walk on the support of excavation if there has no guardrail
3	Edges of excavations (over 2m deep) should be protected with a guardrail
4	People should not stand on machinery when hoisting
5	People should wear a safety harness when working above a certain height
6	There should not use car hopper to pick up people

4.1 Development *of Ontology for FFH*

A taxonomy of hazards related to FFH was developed based on the checklist in Table 2. The core concepts identified are classified and serve as an extension to the taxonomy. For example, a hazard is "There should be no more than two people in a construction man basket". Thus, the hazard entity is 'people' and 'construction man basket'. Activity is 'stand'. Attribute is 'number' and coordinate'. The relationship is 'overlapped/within'.

4.2 Hazard Identification Results

We initially used computer vision to detect objects and their attributes. Individuals, structural support, foundation pit are identified (Figure 3(b) and Figure 3(c)). The spatial relationships of objects are recognized using IoU and distance between objects (Figure 3(c)). As previously mentioned, the results are stored in the Neo4j database (Figure 3(d)) in order to identify unsafe conditions using rule "MATCH (x:laborer)-[r:touch]-(y:structure) RETURN x,r,y" (Figure 3(e)).

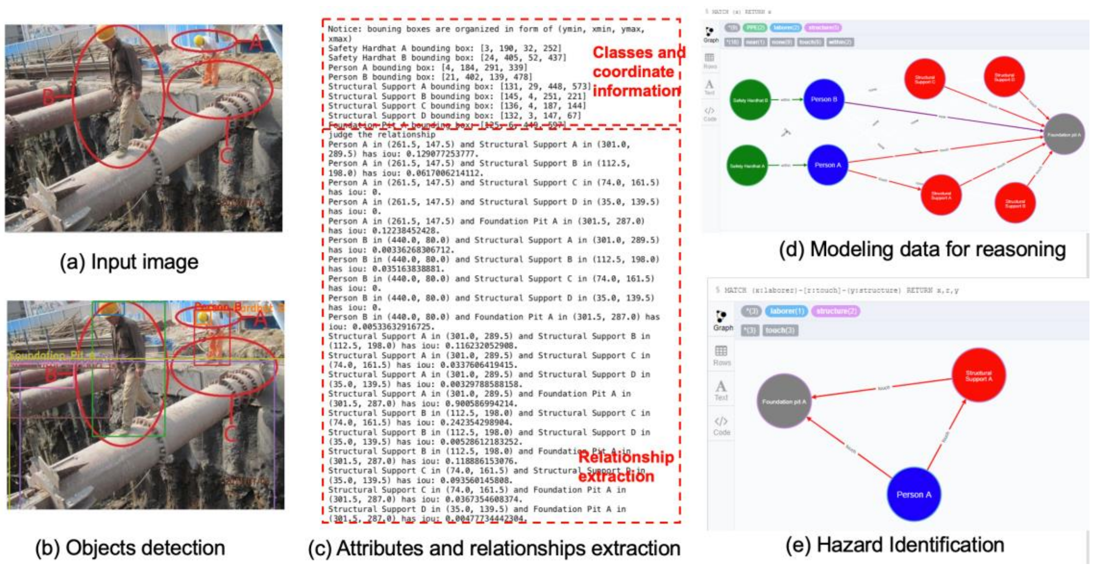


Fig. 3. Semantic computer vision detection results

5. Conclusion, limitation, and future work

We have introduced a novel semantic model to combine computer vision and ontology to automatically identify hazards from images. We utilized the following tools to develop our model: (1) computer vision algorithms which are used to detect objects and attributes; and (2) ontological reasoning to identify unsafe conditions based on the identified distance and spatial information. To validate our approach, a database of FFH from several construction sites is used as a case in our research. It was revealed that our semantic model can accurately recognize safety hazards from images with complex rules. We also suggest that our proposed semantic model can be used by site management to automatically identify potential hazards and therefore put in place strategies to mitigate injuries and accidents.

Despite its success of our approach, it should be acknowledged that several limitations exist. Firstly, our research relied on distance and coordinate information to extract spatial relationship for reasoning hazards. In fact, many hazards comprise safety rules with features. Secondly, our research extracts the coordinates and the distance between objects from 2D images and then obtains spatial-relationship in accordance with the information obtained (i.e., coordinate, distance). Mistakes can be made when using the transformation matrix to compute the distance of objects from single images. Finally, we have also assumed that a variety of objects can be accurately detected by Faster R-CNN. However, if an object is occluded or lack of an available database for training object detection model, the error rate of object detection may be high.

Our future research will focus on: (1) combining temporal information and spatial information to identify construction hazards from videos streaming; (2) using stereo camera to collect data, and compute 3D depth information from stereo videos; (3) combing other information techniques and computer vision to extract more features, such as, size of foundation pit, and colour of safety hardhat, for identifying more types of hazards.

Acknowledgements

The authors would like to acknowledge the financial support provided by the National Natural Science Foundation of China (Grant No.71732001, No.51678265, No.51878311) and the China Scholarship Council (CSC).

References

[1] OSHA, Commonly Used Statistics, https://www.osha.gov/oshstats/commonstats. html2014 (accessed January 17, 2015).

[2] Edwards, H. (2017). “Fatal injuries arising from accidents at work in Great Britain 2017.”

[3] Hadikusumo, B.H.W., and Rowlinson, S., (2002) “Integration of virtually real construction model and design-for-safety-process database”. Automation in Construction. 11(5), 501-509. https://doi.org/10.1016/S0926-5805(01)00061-9.

[4] Martinez-Aires, M., Lopez-Alonso, M., Martinez-Rojas, M., (2018) “Building information modeling and safety management: A systematic review”. Safety Science, 101, 11-18. https://doi.org/10.1016/j.ssci.2017.08.015.

[5] Han, S., and Lee, S. (2013). “A vision-based motion capture and recognition framework for behavior-based safety management”. Automation in Construction, 35, 131-141. https://doi.org/10.1016/j.autcon.2013.05.001.

[6] Han, S., Lee, S., and Peña-Mora, F. (2014). “Comparative Study of Motion Features for Similarity-Based Modeling and Classification of Unsafe Actions in Construction”. Journal of Computing in Civil Engineering, 28, 10.1061/(ASCE)CP.1943-5487.0000339, A4014005.

[7] Ding, L., Fang, W., Luo, H., Love, P.E.D., Zhong, B., and Ouyang, X. (2018). "A deep hybrid learning model to detect unsafe behavior: Integrating convolution neural networks and long short-term memory". Automation in Construction, 86, 118-124. https://doi.org/10.1016/j.autcon.2017.11.002.

[8] Fang, W., Ding, L., Luo, H., Love, P. E. D., and Zhong, B. (2018a). "Falls from Heights: A Computer Vision-based Approach for Safety Harness Detection". Automation in Construction. 91, 53-61. https://doi.org/10.1016/j.autcon.2018.02.018.

[9] Fang, W., Ding, L., Zhong, B.T., P.E.D., and Luo, H. B., (2018b). "Automated Detection of Workers and Heavy Equipment on Construction Sites: A Convolutional Neural Network Approach". Advanced Engineering Informatics, 37, 139-149. https://doi.org/10.1016/j.aei.2018.05.003.

[10] Fang, W., Zhong, B., Zhao, N., Love, P.E.D., Luo, H., Xue, J., Xu, S. (2019). A deep learning-based approach for mitigating falls from a height with computer vision: Convolutional neural network. Advanced Engineering Informatics. 39: 170-177. https://doi.org/10.1016/j.aei.2018.12.005.

[11] Gong, J., and Caldas, C. H. (2009). "Computer vision-based video interpretation model for automated productivity analysis of construction operations". Journal of Computing in Civil Engineering, 24, 252-263. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000027.

[12] Han, K. K., and Golparvar-Fard, M. (2015). "Appearance-based material classification for monitoring of operation-level construction progress using 4D BIM and site photologs". Automation in Construction, 53, 44-57. https://doi.org/10.1016/j.autcon.2015.02.007.

[13] Dalal, N., and Triggs, B. (2005). "Histograms of Oriented Gradients for Human Detection". IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2005. CVPR 2005. (pp. 886-893). https://doi.org/10.1109/cvpr.2005.177.

[14] Wang, H., and Schmid, C. (2014). "Action Recognition with Improved Trajectories". In IEEE International Conference on Computer Vision (pp. 3551-3558). https://doi.org/10.1109/iccv.2013.441.

[15] Memarzadeh, M., Heydarian, A., Golparvarfard, M., and Niebles, J. C. (2012). "Real-Time and Automated Recognition and 2D Tracking of Construction Workers and Equipment from Site Video Streams". International Conference on Computing in Civil Engineering (2012) (pp. 429-436), June 17-20, Florida, United States. https://doi.org/10.1061/9780784412343.0054.

[16] LeCun, Y., Bengio, Y., Hinton, G., "Deep learning", Nature, 521, 436-444.

[17] Luo, X.C., Li, H., Cao, D.P., Yu, Y., Yang, X.C., Huang, T., (2018a) "Towards efficient and objective work sampling: Recognizing workers' activities in site surveillance videos with two-stream convolutional network". Automation in Construction, 94, 360-370. https://doi.org/10.1016/j.autcon.2018.07.011

[18] Luo, X.C., Li, H., Cao, D.P., Dai, f., Seo, JO., Lee, SH., (2018b)"Recognizing Diverse Construction Activities in Site Images via Relevance Networks of Construction-Related Objects Detected by Convolutional Neural Networks", 32(3): 04018012, 10.1061/(ASCE)CP.1943-5487.0000756.

[19] Kim, K., Kim, K., Kim, K., (2017). "Image-based construction hazard avoidance system using augmented reality in a wearable device". Automation in construction, 83, 390-403. https://doi.org/10.1016/j.autcon.2017.06.014.

[20] Elghamrawy, T., Boukamp, F., and Kim, H. S. (2009). "Ontology-Based, Semi-Automatic Framework for Storing and Retrieving On-Site Construction Problem Information — An RFID-Based Case Study". In Construction Research Congress (pp. 457-466). https://doi.org/10.1061/41020(339)47.

[21] Anumba, C. J., Issa, R. R. A., Pan, J., and Mutis, I. (2008). "Ontology-based information and knowledge management in construction". Construction Innovation, 8, 218-239. https://doi.org/10.5220/0003053903310334.

[22] Ding, L. Y., Zhong, B. T., Wu, S., and Luo, H. B. (2016). "Construction risk knowledge management in BIM using ontology and semantic web technology". Safety Science, 87, 202-213. https://doi.org/10.1016/j.ssci.2016.04.008.

[23] Corry, E., Pauwels, P., Hu, S.S., Keane, M., O'Donnell, J., (2015) "A performance assessment ontology for the environmental and energy management of buildings", Automation in Construction, 57, 249-259. http://dx.doi.org/10.1016/j.autcon.2015.05.002

[24] Hippolyte J.L., Rezgui, Y., Li, H., Jayan, B., Howell, S., (2018) “Ontology-driven development of web services to support district energy applications”. Automation in Construction, 86, 210-225. http://dx.doi.org/10.1016/j.autcon.2017.10.004.

[25] Zhou, Z.P, Goh, Y.M., Shen, L.J. (2016). “Overview and Analysis of Ontology Studies Supporting Development of the Construction Industry”. J. Computing in Civil Engineering, 30(6), 10.1061/(ASCE)CP.1943-5487.0000594, 0406026.

[26] Dong, Z. and Dong, Q. (2003). HowNet – a hybrid language and knowledge resource. Proceedings of the International Conference on Natural Processing Language and Knowledge Engineering, 26-29th October, IEEE, Beijing, China, 10.1109/NLPKE.2003.1276017

[27] Dong, Z., Dong, Q., (2006) “HowNet and the computation of meaning”, World Scientific Publishing Co., Inc., https://doi.org/10.1142/9789812774675.

[28] Goh, Y. M., and Chua, D. K. H. (2010). "Case-Based Reasoning Approach to Construction Safety Hazard Identification: Adaptation and Utilization." Journal of Construction Engineering and Management, 136(2): 170-178. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000116.

[29] Guo, B. H. W., and Goh, Y. M. (2017). "Ontology for the design of active fall protection systems." Automation in Construction, 82(Supplement C), 138-153. https://doi.org/10.1016/j.autcon.2017.02.009.

[30] Xiao, T., Liu, Y.C., Zhou, B.L., Jiang, Y.N., Sun, J., (2018) “Unified Perceptual Parsing for Scene Understanding” Lecture Notes in Computer Science, 432-448. https://doi.org/10.1007/978-3-030-01228-1_26.

[31] Johnpaul, C.I., Mathew, T. (2017). “A cypher query based NoSQL data mining on protein databases using Neo4j graph database” 4th International Conference on Advanced Computing and Communication Systems. Coimbatore, India. https://doi.org/10.1109/ICACCS.2017.8014558.

[32] Guia, J., Soares, v. G., Bernardina, S., (2017) “Graph Database: Neo4j Analysis”, Proceedings of the 19th International Conference on Enterprise Information System, 351-356, Porta, Portugal. https://doi.org/10.5220/0006356003510356.

Using UAV-generated Visual Contents to Assess the Risk Perception of Safety Managers on a Construction Site

Jhonattan G. Martinez[1]*, Masoud Gheisari[2], Luis Fernando Alarcón[1], Roberto Mauricio Luna Guzman[1]

[1] Pontificia Universidad Católica de Chile

[2] University of Florida

* email: jgmartinez1@uc.cl

Abstract

To avoid accidents on site, safety planning plays a crucial role in the construction domain. It consists of risk identification and making proper decisions about the safety measures required to be implemented during the construction phase. This safety planning process heavily relies on safety managers' risk perception capabilities. These capabilities would help safety managers to anticipate the accidents or incidents before they occur on the job site. Safety managers' risk perception capabilities are affected by variables such as years of safety experience, professional safety training, and more importantly the site information and the visual content used for safety planning (e.g., schedules, 2D drawings). One of the technologies employed for gathering visual information of the project sites is the Unmanned Aerial Vehicle (UAV), which is a generic type of aircraft designed to operate without a human pilot onboard. UAV can be deployed to send visual information (e.g., photos and videos) of the job site and specifically inaccessible, hard-to-reach, or unsafe locations on the site to the safety managers, faster and more efficiently. These types of visual information can be transformed through a photogrammetry process into point cloud data (PCD) and then be used to generate an accurate 3D model of a site that provides very detailed and comprehensive view of a project site. In this case study project, we focus on how visual content generated by UAVs (including photos, videos, PCDs, and 3D models) can affect the risk perception of safety managers. A comparison between the UAV-based safety monitoring process vs. the traditional one (using conventional information) was conducted in a case study in Chile and risk perception of safety managers under both methods were evaluated. The study concluded that the use of UAV allows to identify more hazards and increases the safety managers' perception of severity, probability, and risk level of hazards on site**.**

Keywords: unmanned Aerial Vehicle (UAV), Safety, Risk Perception, Construction

1. Introduction

The number of accidents and deaths continues being a problem that needs to be eradicated from the industries around the world. One of the sectors that present the highest rate of accidents is construction (M. Zhang et al. 2013). Approximately, the accident rate in this industry is four-time higher than the average of other sectors. Because of that, safety has become one of the essential aspects of many construction projects. In Chile, a study conducted by the Superintendencia de Seguridad Social (2017) suggested that during 2017, the rate of accidents in the construction industry was 4.1 per every 100 workers. In the same year, 44 workers died on the job; this represents 20% of all the deaths occurring across different industries. The leading causes of workers' deaths were falls (36%), struck by objects (8%), electrocution (7%) and caught-in/between (6%) (Superintendencia de Seguridad Social, 2017). These hazards led to an average of 23.4 working days lost for each accident during the year (Superintendencia de Seguridad Social, 2017).

The construction industry is characterized for generating low-severity accidents with higher frequency, and additionally, have several sources of risk (Zhou et al. 2015). Because of that, several construction companies consider safety management as one of the main factors associated with reducing costs for work-related accidents and injuries (Hinze, 2002). It consists of a series of steps such as hazard identification, risk assessment, and risk management, each one considered key for the success of the projects. Beside of this, hazard identification activities are carried out to identify and localize the sources of hazards et al. 2013), risk assessment provides indexes that support decisions about how to manage (Lee et al., 2012) and risk management combines efforts to manage risk through risk estimation, risk evaluation, and risk-based decision making and design improvement (Khan et al. 2015).

A factor that directly affects the hazard identification and safety monitoring is the safety manager's risk perception capabilities (Zuluaga et al. 2016). Gürcanli et al. (2015) defined it as a subjective judgment that people make about the frequency and severity of risks. The perception is usually measured by surveys that are applied individually to professionals and workers in order to evaluate scenarios with specific risks. Improving the perception is essential due to several injuries have been linked to poor hazard recognition and safety planning (Khan et al. 2015).

The risk perception depends on variables such as experience, training, and the quantity and, quality of visual information available, among others (Namian et al. 2016). Generally, the safety manager use project technical information such as 2D plans, schedules, and photos to identify and assess the potential risks and its consequences, in other words, traditional method (Zhang et al. 2015).

One of the technologies employed for gathering visual information on the site is the unmanned aerial vehicle (UAV), which is a generic type of aircraft designed to operate without a human pilot onboard. A UAV can be deployed to send visual information (e.g., photos and videos) of the job site as well as inaccessible, remote, unsafe, or hard-to-reach locations to the safety manager faster and more efficiently and help with safety-related data collection and decision-making processes. The job site photos and videos captured by a UAV can also be transformed through a photogrammetry process into point cloud data (PCD) and then be used to generate a 3D model that offers a complete view of the job site from different visual perspectives.

This study presents a case study conducted in Chile where we compare the traditional method with the UAV-based method of conducting safety planning and monitoring on a construction site in Chile and evaluate the risk perception of safety managers using both methods. It is envisioned that a UAV-based approach might allow the safety managers to improve their risk identification process and reduce the manual efforts to capture data that are utilized to measure hazard indicators during the construction phase

2. Research Method

For this research project, a case study strategy was adopted. It consists of detailed observation of a case subject to identify practical problems and situations. Using this methodology, it is possible to capture the complexity of a single case and potentially generalize the results to other conditions or circumstances (Rolf Johansson, 2003; Yin, 2009). The research was conducted in a residential location in Santiago, Chile. This project was a high-rise residential building which included four 23-story and two 6-story buildings with a land area of 16,850 m^2. This project was selected because of its safety monitoring complexities and challenges due to work conducted at a high altitude and a congested area with a very limited number of safety managers on board. Two safety planning approaches were used in this case study, and safety managers' risk perception was assessed and compared under each method. The research method consisted of the following three steps:

(1) The Traditional Method consists of developing the safety planning process using project and job site information such as plans, schedules, and photos. Safety managers use such information to determine possible risks and assess their probabilities and consequences. For the research purpose, technical plans, and weekly schedule that were implemented during the construction stage were used. The safety managers used these contents to evaluate the possible risks and assess their probabilities and consequences on the same site.

(2) The UAV-based Method consists of developing the safety planning process using project and job site information that was previously used in the traditional method together with visual content captured by UAVs such as photos, videos and generated 3D models. Then, safety managers use the data generated by UAVs to determine the possible risks and assess their probabilities and consequences on the same site. The 3D models generated are part of the data set used to evaluate the safety managers risk perception, together with photos and videos captured by the UAV. During the data collection, the job site was photographed to obtain horizontals and oblique photos and after that transforming into job site 3D models through photogrammetry technique using the software Drone Deploy. These processes were conducted during the five job site visits. The parameters used to process the 3D models are also elaborated in Table 1

(3) Traditional vs. UAV-based Comparison: Traditional based method and the UAV-based method were compared to determine the safety manager risk perception in both scenarios. The variables evaluated and analyzed for the comparison were as following:

- **Severity** indicates the level of consequence generated by an accident measured in scale of no injured to fatal injured were evaluated using a scale from one to five, where five in the case of accident severity is No Injury, and one is Fatal.
- **Probability** of occurrence refers to the possibility that an unwanted event occurs and can produce consequences. It is measured in the scale of infrequent to frequent
- **Risk level** is the multiplication of the probability that occurs an unwanted event and the severity level. It is measured in the scale of very low to very high-risk level was implemented.

3. Data Collection

A total of five visits were conducted for both traditional and UAV-based methods. Figure 1 shows the project status during each visit.

Site Visit #1	Site Visit #2	Site Visit #3	Site Visit #4	Site Visit #5

Figure 1: Site Visits

For the data collection process, the project team followed the flight regulations established by the Dirección General de Aeronáutica Civil (DGAC) that control UAV flights in Chile. Under the standard DAN 151, the general requirements indicated are the following (Dirección General de Aeronáutica Civil, 2015):

(1) UAV should be registered in the DGAC portal,
(2) UAV pilot should be licensed to operate the vehicle for professional purposes,

(3) the maximum allowable altitude is 130 meters above ground level, and
(4) the maximum allowable operating horizontal distance between the UAV and the pilot is 500 meters.

To collect the data a DJI Phantom 4 Pro UAV was selected. It was chosen due to the quality of its camera, its battery life and included sensors that allow for making safer flights near objects such as cranes, trucks, scaffolds, and guardrails on the project site. This UAV has a camera lens with an 84° field-of-view and with a 1-inch 20-megapixel sensor capable of shooting 4K/60 fps video at 100 Mbps (DJI, 2017).

DJI Phantom 4 Pro

Pilot conducting the flight Data Collection

DJI Phantom 4 Pro on the site

Figure 2: UAV Platform and Data Collection on Site

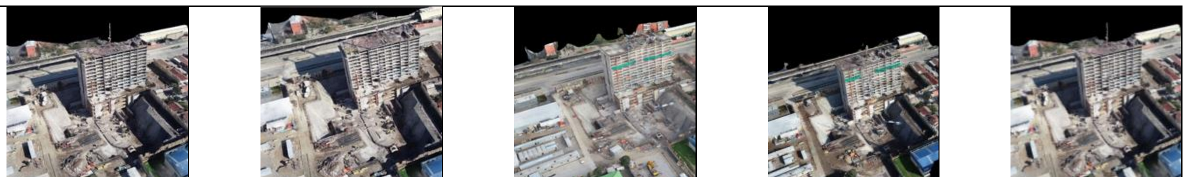
The next table show the amount of data collected during this process:

Table 1: Data collection

Parameters (Unit)	**Site Visits**				
	#1	**#2**	**#3**	**#4**	**#5**
Building height (meters)	60	63	66	66	66
Flight height (meters)	76	75	73	73	73
Flight start time (24 hr)	12	14	10:30	10:30	10:30
Flight duration, for taking pictures only (min:sec)	8:42	10:18	15:03	15:03	15:03
Frontal overlapping (%)	79	79	82	82	82
Lateral overlapping (%)	84	84	82	82	82
GSD resolution (centimeters/pixel)	2.3	2.2	2.0	2.0	2.0
Flight speed (meters/second)	15	15	15	15	15
Number of photos	122	161	267	267	267
Number of additional vertical photos	15	15	15	15	15

Parameters (Unit)	Site Visits				
	#1	#2	#3	#4	#5
Flight duration, for taking videos only (min:sec)	34:34	42:12	45:45	42:23	38:21
Weather conditions	Cloudy	Sunny	Sunny	Sunny	Cloudy

A total of 46 video clips and 1159 photos were captured throughout the five site visits to generate the 3D point clouds using Drone Deploy's ® photogrammetric capabilities. Drone Deploy is a cloud-based system that allows for sharing its outcomes with other groups involved through the web and allows for the development of point cloud data through a cloud-based photogrammetry process. To improve the quality of the generated 3D model, fifteen frontal and vertical photos were added to the photogrammetry process to increase the visual content overlap on the sides of the building. The models created were carefully reviewed to minimize visual inconsistencies produced by insufficient horizontal and vertical overlapping, photo set quality or moving objects. Because of that, these models offered an accurate representation of the job site and, provides a complete view from different visual perspectives of them. In total, five 3D models were generated after the end of each site visit (see Figure 3).



Site Visit #1	Site Visit #2	Site Visit #3	Site Visit #4	Site Visit #5

Figure 3: 3D models developed after each site visit

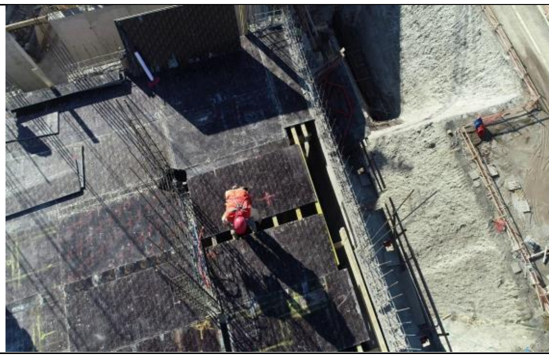
4. Comparative Results and Discussion

Two safety managers with nine and seven years of on-site risk prevention experience were in charge of safety inspection and monitoring for this project. At the end of each week of data collection, the safety managers were asked to examine construction documents (plans and schedule) and a set of photos, videos, and 3D model took at the job site. First, the traditional method was evaluated, and then after around thirty minutes, UAV-based method was assessed. The risk perception evaluation of each method took around one hour. As a first step of the research, the number of hazards identified was determined using the traditional method and then the UAV method. After this, the severities, probabilities of occurrence, and the risk levels of the identified hazards were determined, and these quantities were averaged utilizing both methods. The following table shows the results consolidated:

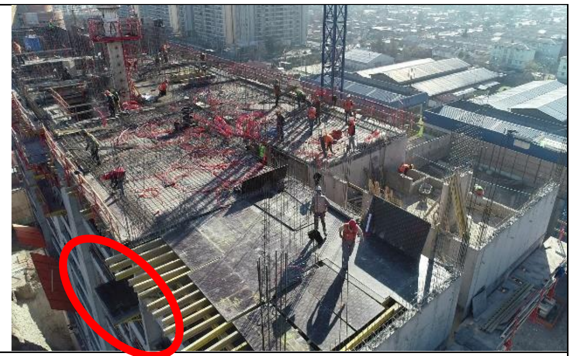
Table 2: Risk perception data analysis.

Variables	Site Visit #1		Site Visit #2		Site Visit #3		Site Visit #4		Site Visit #5		Average	
	Traditional	AV	Traditional	AV	Traditional	AV	Traditional	AV	Traditional	AV	Traditional	AV
Hazards identified (#)	19	22	16	18	22	26	15	19	17	21	17.8	21.2
Severity	3.3	3.5	2.9	3.1	3.7	3.6	3.2	3.3	2.8	2.9	3.18	3.28
Probability	3.8	4.1	3.3	3.6	4.1	4.2	3.5	3.7	3.2	3.5	3.58	3.82
Risk level	3.7	3.9	3.6	3.7	3.9	3.8	3.4	3.8	3.1	3.6	3.54	3.76

Regarding identified hazards, the use of UAV-based methods allowed for the identification of more hazards than the traditional method. On average, using this method, it was possible to increase the number of identified by up to 19% hazards in the workplace. Figure 4 shows some examples of the identified hazards in the UAV-based method.

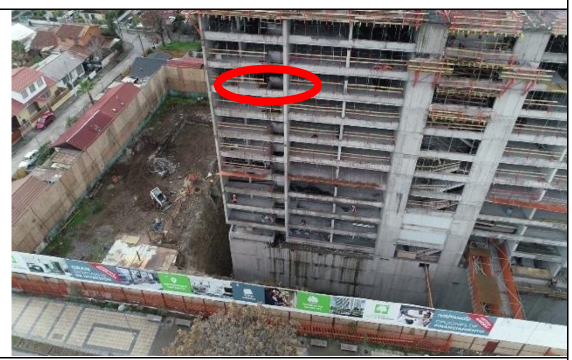


A worker in close proximity to openings and edges



Lack of guardrails

Worker without safety rope



Lack of guardrails

Figure 4: A few hazards identified in the visual content captured in UAV-method

On the other hand, the severity assessment using the UAV-based method for all the identified hazards increased compared to the traditional method by up to 3%. The probability of occurrence of the identified hazards, as with the other variables, increased by 7% using the UAV-based method due to the safety managers' access to a job site panoramic view using the 3D models generated by the UAV. Finally, the risk level increased by 6% on average using the UAV-based method (except for site visit # 3).

Focusing only on safety hazard types, it was noticed that using UAV-based method; the safety manager could better identify the following unsafe conditions and safety measures:

- Lack of Guardrails (Fall Hazards): The 3D models generated by UAV provided a very precise representation of the job site status and allowed the safety managers identify the presence and assess the proper installation of the guardrails through accurate measurements directly in the captured models.
- Lack of Safety Nets (Fall Hazards): Safety Nets are usually located in hard-to-reach zones (e.g., top of the buildings) where it is hard, unsafe, or impossible for safety managers to visually inspect. The visual contents captured by UAVs (especially videos and images) allowed the safety managers to identify the areas such as unprotected exterior boundaries of slabs or balconies that might be required to be protected by safety nets as well as inspecting the proper installation of current safety nets and their proper coverage of the targeted areas
- Moving/Falling Objects (Struck-by Hazards): The aerial images captured by the UAV allowed the safety managers to see better the moving objects (e.g., tower cranes or machineries) or

objects with potential to fall (e.g., loose or unsecured material at height) that might create potential struck-by hazards on the jobsites.

- Lack of Personal Protective Equipment (PPE): The aerial videos captured by the UAV allowed the safety managers to detect several violations regarding improper or lack of personal protective equipment (PPE) and safety harnesses use on the site including several unsafe acts such as not wearing the hard hats or safety glasses.
- Evacuation Route: The aerial images and the 3D models generated by UAVs allowed the safety managers to identify areas without proper evacuation route demarcation.

5. Conclusions

The primary objective of this study was to compare the risk perception of safety managers using traditional and UAV-based safety monitoring processes considering variables such as the number of risks, severity, probability of occurrence, and risk level using a case study in Chile. The case study results showed that the adoption of this technology as a tool for safety planning and monitoring allows for better identification and evaluation of hazards compared with the traditional method. The case study demonstrated that the use of UAVs allows for the identification of up to 19% more hazards during the safety planning stage. Furthermore, safety monitoring using UAVs automates the efforts of capturing proper onsite information and allows for frequent monitoring and safety challenge measurement on site. To properly apply the technology, the safety manager needs to establish the flight plans to collect the appropriate amount of data required for their safety monitoring process. Currently, fully automating the manual onsite observation with UAVs is difficult due to aviation regulations and limitations, weather conditions, and the limited UAV flight times. Using UAVs for safety monitoring on the job site is at a very early stage of development and implementation, and further studies on the legal, financial, safety, as well as hardware and software development aspects of UAVs, needs to be conducted for the successful implementation of UAVs to facilitate safety monitoring on construction job sites

References

Al Nahyan, M. T., Hawas, Y. E., & Raza, M. (2019). An exploratory study of relationships between stakeholders' risk perceptions and their roles and experience in construction industry. *International Journal of Construction Management*, *0*(0), 1–16. https://doi.org/10.1080/15623599.2019.1580833

Alizadehsalehi, S., Asnafi, M., Yitmen, I., & Celik, T. (2017). UAS-BIM based Real-time Hazard Identification and Safety Monitoring of Construction Projects Use of Immersive BIM for Design and Construction View project VR/AR/MR View project. In G. L. and C. R. Martine Buser (Ed.), *9th Nordic Conference on Construction Economics and Organization* (pp. 22–32). SWEDEN: Chalmers University of Technology, Göteborg.

Dirección General de Aeronáutica Civil. (2015). *Dan 151: Operaciones de aeronaves pilotadas a distancia (RPAS) en asuntos de interés público, que se efectúen sobre áreas pobladas*. 17.

DJI. (2017). *Phantom 4 Pro/Pro + User Manual*. 67. https://doi.org/10.1007/SpringerReference_28001

Gürcanli, G.., Baradan, S., & Uzun, M. (2015). Risk perception of construction equipment operators on construction sites of Turkey. *International Journal of Industrial Ergonomics*, *46*, 59–68. https://doi.org/10.1016/j.ergon.2014.12.004

Hinze, J. (2002). *Making Zero Accidents a Reality*. CII Research Rep 160-11, The University of Texas at

Austin, EEUU.

Khan, F., Rathnayaka, S., & Ahmed, S. (2015). Methods and models in process safety and risk management: Past, present and future. *Process Safety and Environmental Protection*, *98*, 116–147. https://doi.org/10.1016/j.psep.2015.07.005

Lee, H., Asce, M., Kim, H., Park, M., Ai, E., Teo, L., & Lee, K. (2012). *Construction Risk Assessment Using Site Influence Factors*. (June), 319–330. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000146.

Man Li, R. Y., & Poon, S. W. (2013). *Constuction Safety*.

Namian, M., Albert, A., Zuluaga, C. M., & Behm, M. (2016). Role of Safety Training: Impact on Hazard Recognition and Safety Risk Perception. *Journal of Construction Engineering and Management*, *142*(12), 04016073. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001198

Rolf, J. (2003). Case study methodology. Retrieved February 3, 2019, from https://www.researchgate.net/publication/236143987_Case_study_methodology

Superintendencia de Seguridad Social. (2014). *Estadísticas de Accidentabilidad 2013*. Santiago: Superintendencia de Seguridad Social.

Yin, R. (2009). Case study research : design and methods. In *Applied social research methods series ;* https://doi.org/10.1097/FCH.0b013e31822dda9e

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., & Teizer, J. (2015). BIM-based fall hazard identification and prevention in construction safety planning. *Safety Science*, *72*, 31–45. https://doi.org/10.1016/j.ssci.2014.08.001

Zhou, Z., Goh, Y. M., & Li, Q. (2015). Overview and analysis of safety management studies in the construction industry. *Safety Science*, *72*, 337–350. https://doi.org/10.1016/j.ssci.2014.10.006

A knowledge-based Approach for the Assessment of Damages to Constructions

Al-Hakam Hamdan* and Raimar J. Scherer,
Institute of Construction Informatics, TU Dresden
* email: Al-Hakam.Hamdan@tu-dresden.de

Abstract

To assess detected anomalies as well as assume undetected damages of an existing construction, a knowledge-based approach for damage evaluation is presented, whereby data from multiple web ontologies are linked via Linksets that are stored in an Information Container for Data Delivery (ICDD)[1]. In the ICDD, an ontological model that represents the assessed construction is linked with a damage ontology, which is necessary to identify various damage types that could affect the construction. Additionally, the web ontology representing the construction is linked with a Building Information Model (BIM) in the IFC-Format to enable access to the geometrical data of the components. Similarly, the damage objects are linked with either recorded geometry data or a manually created geometry model. Predefined rules are applied on the assertion components of the web ontology for reasoning damage types of each detected anomaly and damage assessment. Furthermore, the existence of undetected damages can be reasoned based on information about the construction, environment and previously classified damages. The developed web ontologies in this research use the principles of Linked Data and are serialized in the data format OWL. This enables the utilization of already existing Linked Data ontologies as well as supporting the implementation and development of future ones.

Keywords: Damage Classification, Building Information Modeling, Construction Assessment, Ontologies, Linked Data

1. Introduction

Technological Advancements in the field of anomaly detection in structures enable the utilization of tools and systems that can process an automatic identification and localization of defects and structural damages, which physically harm existing constructions so that their structural capacity, durability or usefulness is impaired. However, the classification of these anomalies and the reasoning of undetected damages (e.g. overseen or unreachable ones) is performed manually by an expert. Additionally, after the classification process is finished, it is necessary that the expert evaluates the damage by considering properties, which have an influence on the maintenance of the construction, e.g. impacts on the structural capacity, durability or traffic safety. For this purpose, standards are used in certain countries, e.g. DIN 1076 in Germany (BVBS, 2007) which use a grading system to assess the damages and determine the overall condition of the construction. However, in using these standards, the damage assessment is often simplified to assigning a generalized grade or limited number of condition indexes. A detailed classification and identification of the damage cause is often only recorded in non-machine interpretable or even non-digital formats, e.g. handwritten inspection protocols or images, thus further processing and managing of these data, especially in later lifecycle stages of the construction is more difficult. Furthermore, for analyzing more accurately the structural capacity of the construction it is necessary to model the system in a damaged state according to principles in structural analysis such as the smeared crack approach ((Bažant & Oh, 1983). However, the exact mechanical

[1] https://www.iso.org/standard/74389.html

parameters, which characterize the damage are not derivable. For this purpose, a simulation-based system identification is required, where additional measurement data are utilized, which reflect the behavior of the construction under known load (Luu, Hamdan, Polter, Scherer, & Mansperger, 2018). Thereby, the damage parameters need to be variated in order to identify a system that fits best to the monitored structural behavior. Thus, using this approach, it would be possible to estimate more precisely suitable refurbishment methods for existing constructions. However, manual definition of damage parameters would be very time consuming and not feasible in an appropriate time without automation. Therefore, in this research a computer-based approach for damage classification and assessment has been developed which utilizes Semantic Web technologies for inferring properties from detected anomalies. Anomaly data, which can be either created manually or by utilizing appropriate tools are used for creating a web ontology using the Web Ontology Language (OWL)[2] as data format. Thus, OWL supports the application of inference mechanisms based on description logic through reasoning engines as well as modelling the information in a graph which uses Unique Resource Identifiers (URI) for identifying each dataset. By using rule languages such as SWRL, DROOLS or SHACL, classification and evaluation rules are defined which are then applied on the anomaly data. Consequently, a presumption of undetected damages as well as identifying the reduced mechanical parameters is processed by analyzing the information from semantic reasoning in combination with a numerical structural analysis. In this context, the workflow can be utilized as part of the BIMification process (Scherer & Katranuschkov, 2018), where an in depth survey of damages is an important step. In this paper, the concept of the approach is explained on a detailed workflow. In addition, the utilized web ontologies and linked models are described. Furthermore, the concept of applying rules for classification, evaluation and assumption is presented, using specific examples from maintenance of reinforced concrete bridges.

2. Related Work

Systems for the automated classification of defects have already been developed in other fields, such as (Patent No. US5544256A, 1996), where a fuzzy logic inference engine is utilized to classify object defects in various products. Concerning constructions in civil engineering, various approaches regarding damage classification and assessment focus on utilizing machine learning. Thereby, the Nanjing HuoYang Hou Mdt InfoTech Ltd. developed a system that detects various damages in metro tunnels and analyze them by processing automatic machine recognition and quantitative damage analysis (Huang, Fu, Chen, Zhang, & Huang, 2018). Another notable approach uses support vector machines for the recognition and evaluation of bridge cracks (Li, Zhao, Du, Ru, & Zhang, 2017). All these approaches have in common that a large amount of training data is needed as a prerequisite to get accurate results by using machine-learning methods. Therefore, a method for classifying building defects with case-based reasoning has been developed by (Xu, Li, Li, & Li, 2018), which requires a comparatively smaller number of reference subjects.. Other approaches have also been developed using Semantic Web technologies. In this regard, (Lee, Chi, Wang, Wang, & Park, 2016) proposed an ontology-based system for querying specific defect cases based on construction conditions, which were derived from a BIM model. Furthermore, an ontological model has been developed in the research project MONDIS, which defines damage causations and corresponding damage properties for historical constructions and thus can also be used for damage classification and assessment (Cacciotti, Blaško, & Valach, 2015). An approach which enhances the reasoning process with SWRL rules has been elaborated by (Ren, Ding, & Li, 2019). Thereby, the rules are used for applying condition indexes to detected cracks and therefore process a damage assessment.

Despite these various developments in the field of machine-based damage classification and evaluation, no approach exists at the time of this publication, which assumes undetected or hidden damages in existing constructions.

[2] https://www.w3.org/OWL/

3. Workflow of Damage Assessment

The objective of the knowledge-based damage assessment is the creation of a damage map that includes both the previously detected damages and undetected suspected damages, which have a negative impact on the structural capacity of the construction. The workflow in Figure 1 depicts how this damage map is created and serialized as an ontological model in OWL.

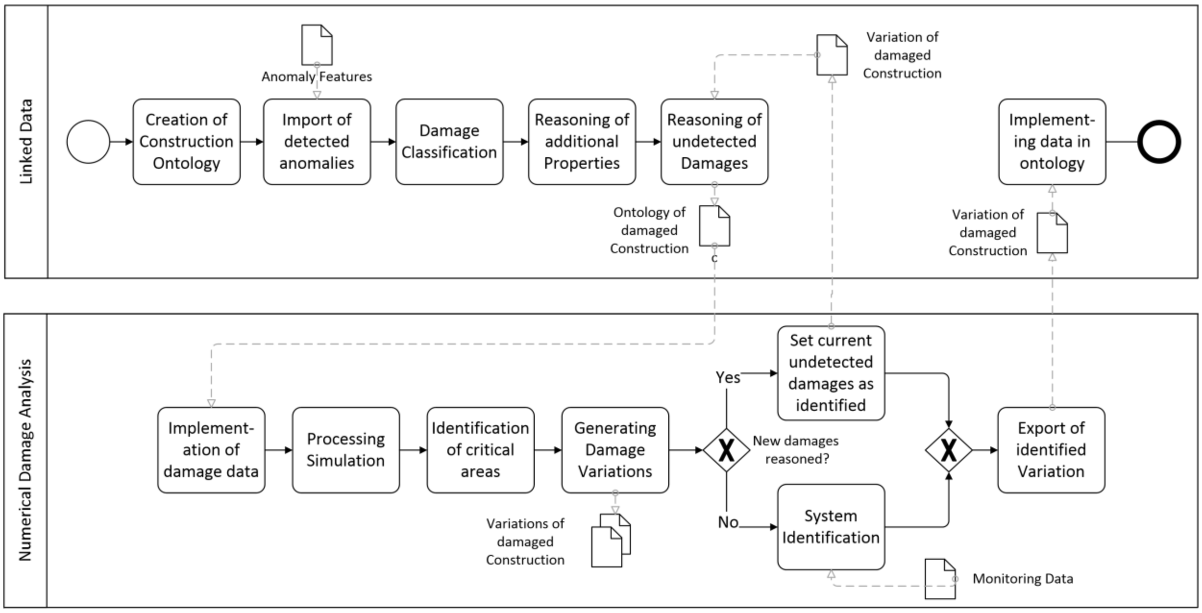


Figure 1 Workflow of the knowledge-based Damage Assessment

In addition to semantic reasoning, a numerical analysis is utilized to reduce the range of possible locations for assumed damages in the resulting damage map. However, besides the numerical approach, other ways of identifying an assumed damage are also possible, e.g. through an additional inspection with detection tools or material tests.

Before a knowledge-based damage assessment can be processed, an ontological model representing the affected construction needs to be created. In this regard, existing construction ontologies such as the Building Topology Ontology (BOT) (Rasmussen, Pauwels, Hviid, & Karlshøj, 2017) can be utilized as a core ontology for defining the topology of the construction and their aggregated elements and zones. Together with domain specific extensions, a data representation of the affected construction can be modeled, which supports knowledge-based operations.

Subsequently, a web ontology is produced based on previously recorded damage data. The damage recording process is not bound to a specific data format. For instance, data from detection tools can be used as well as manually recorded damage descriptions by an inspector. However, it is important that the data is stored in a machine-readable format and that the damage characteristics are filterable for implementation in the web ontology. In this regard, approaches for machine-based damage detection such as by (Morgenthal et al., 2019) are suitable for importing detection data to a web ontology for damage representation, since these data are modelled as feature values, which can be processed immediately. Since images and descriptions made by humans are not machine-readable, a direct input to a web ontology via an optional graphical user interface is recommended for manual damage recording.

When an initial damage representation has been created as web ontology, further reasoning via inference mechanisms and predefined rules can be applied to classify the recorded anomalies. In a similar way additional properties such as mechanical or assessment parameters are derived based on the damage classifications. Additionally, it can be inferred whether undetected structural damages could exist and which potential component types they could affect. However, locations or specific values cannot be derived. Therefore, further numerical data processing is necessary to identify the assumed damages. The information from the construction and damage ontology are used to generate a structural analysis model that can be used to identify critical areas, where a damage occurrence is probable due to overload and could lead to a significant reduction of the structural capacity. Thereby, damages are mapped to the structural analysis model as areas with reduced material parameters using the smeared crack approach (Bažant & Oh, 1983). A mapping of cracks using the discrete crack approach could also be possible, however due to the more complicated modeling and data processing this method has not been investigated in this research. Since it is not sure whether damages occur in the critical areas identified in the simulation process, different variants are created that combine multiple damaged areas with each other as well as variate their related mechanical properties. Thereby, the results from the semantic reasoning in the ontology are considered, to reduce the amount of possible damage variants by a significant amount. The identified damages in each variant could then lead to new assumed damages, by applying assumption rules while considering the previously concluded damages. For this reason, the variants are inferred again in the ontology and evaluated in the numerical simulation in an iterative process until no new damages occur. The resulting variants are then evaluated against monitored data of the construction behavior under the same loads as in the simulation, thus a system identification can be processed and the best fitting variant of the damaged structure is identified (Luu et al., 2018). Since, the process requires a lot of computing performance, the generation of variants and system identification in this method has to be highly automated. This has not yet been tested and validated to its full extend. However, it is possible to realize the proposed method by utilizing new Grid or Cloud technologies. For that purpose a BIMgrid framework was developed by (Polter & Scherer, 2018).

Finally, the best fitting variant of the damaged construction is serialized as resulting damage map in OWL for future damage information management.

4. Structure of the Damaged Construction Ontology

For the mere knowledge processing, only information is necessary that describes the existing construction and the associated damages, which can be stored in one or multiple web ontologies. This information is often present in other models or documents. Within the scope of BIM, the Industry Foundation Classes (IFC) is an established standard for storing construction information and interlinking it with a geometrical representation. Equivalent sets of information between the IFC model and the construction ontology are identified and linked together by using the ICDD. Linking other resources with the ontology, e.g. inspection reports or images is possible and recommended for a comprehensive data management. In a similar way, the damage ontology is linked with a geometrical representation utilizing common formats.

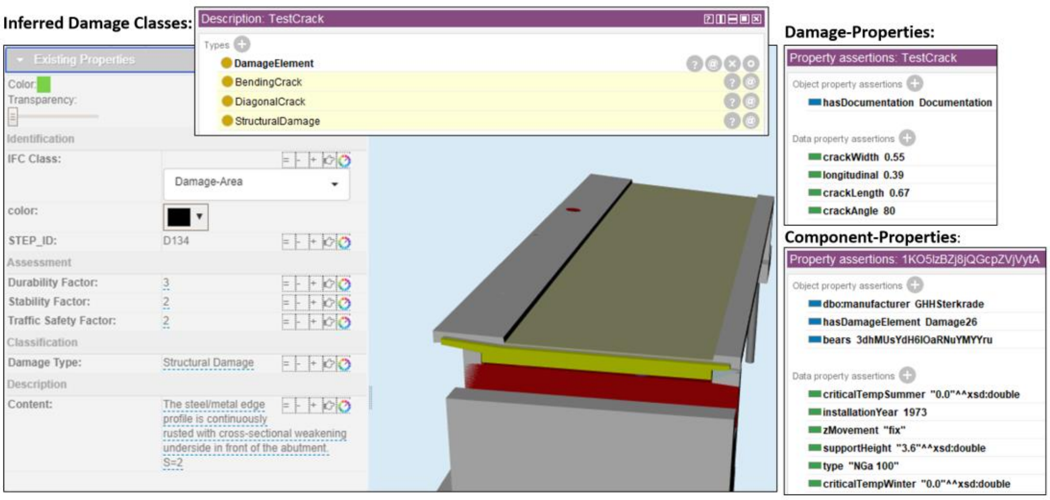


Figure 2 Visualisation of Damaged Construction (ifcwebserver.org) & Ontology Information

4.1 Construction Ontology

The structure of the ontology that represents the existing damaged construction varies and is always strongly dependent on the construction type and the requirements for the specific use cases. The web ontology should consist of metadata about the construction, its history and environmental influences as well as about their aggregated components. Additionally, information about the used building materials is necessary, since the type of damage that could affect a structure is heavily dependent on the used material. Furthermore, structural analysis information about the construction and components is recommended for a more streamlined mapping of the ontology to a FE model or other type of structural analysis model. Consequently, the construction ontology should consist of a topology, classifications for bridges and their aggregated components and material as well as structural analysis information. The IFC model is mainly used for holding the graphical data of each component and the entities are linked with the semantic data from the bridge ontology, so that the resulting ICDD could be graphically as well as semantically processable, provided that appropriate software for this application is developed.

4.2 Damage Ontology

The damage ontology uses terminological components of the Damage Topology Ontology (DOT) (Al-hakam Hamdan, Bonduel, & Scherer, 2019) to define a core ontology for damage representation, which is based upon the Generic Damage Model approach (A Hamdan & Scherer, 2018). Thereby, DOT defines digital *Damage Elements*, which can be aggregated via using a specific object property in a *Damage Area* that represents damages at a lower detail level. Furthermore, *Damage Elements* inside a *Damage Area* can be marked as physically connected objects, either by concatenating them with certain object properties or grouping them by utilizing a specific *Damage Pattern* class.

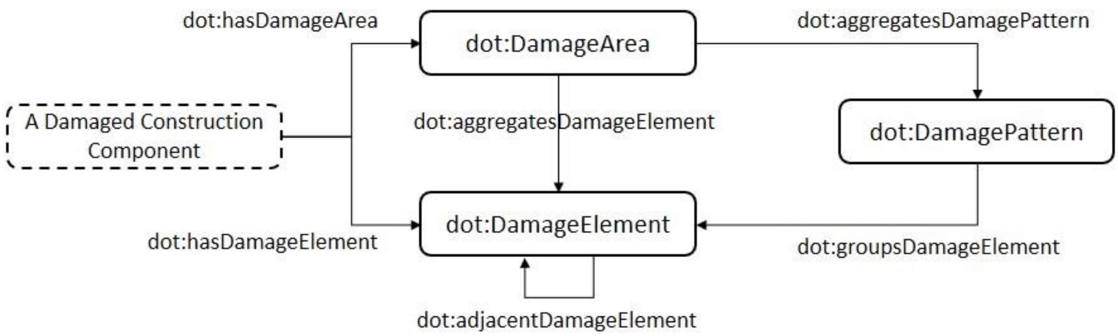


Figure 3 Topological components of DOT (Al-hakam Hamdan et al., 2019)

Besides topological definitions, simple classifications regarding the impact on the structural capacity of a construction for each damage object are supported by differing between structural damages and defects. While structural damages have a negative impact on the structural capacity, this does not apply to defects. However, defects can affect the durability, traffic safety or other factors in a negative way. Additionally, simple descriptions or external documents can be put in relation to the damages in conjunction with additional metadata (e.g. author, date of inspection, etc.). Therefore, DOT can be used as a standalone ontology for storing damage representations and managing them. However, more specific attributes that describe damages of certain types, e.g. the width of a concrete crack, are not covered by DOT. In order to solve this problem, DOT is extended by further terminological components that reflect domain specific knowledge about damage to specific materials or components. Thus, this research the core ontology has been extended with definitions about damages which occur in reinforced concrete as well as about damages that affect bridge components. One feature of these extensions is that they only define new classes for classifying damage in the form of taxonomies, and data properties that characterize these new damage types, thus ideally, no new object properties are added. *Figure 4* shows an example of the taxonomy from the ontology extension for damage classification in reinforced concrete, including the associated data properties.

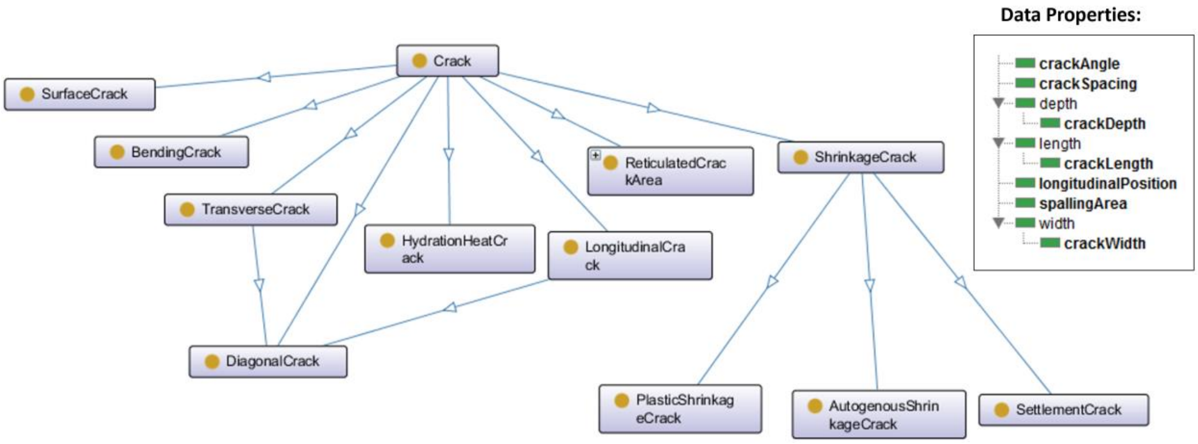


Figure 4 Taxonomy and Data Properties of an ontology extension for damages in concrete.

An exact geometry, as it is used with independent geometry models for visualization, is not defined in the ontology, because the data used for a geometrical representation would be inefficiently stored in an RDF file compared to data formats like Wavefront, Collada or IFC. Furthermore, despite approaches for defining geometry in Linked Data exists, such as by (Pauwels, 2017) or (Shaya, n.d.), no visualization tool exists for processing these data. Because of this, an approach similar to the geometrical representation of the construction ontology is used, whereby a separate geometry model in a data format that is processable by common visualization tools is used and linked with the damage ontology by utilizing the ICDD. Therefore, the URIs of the damage representations from the ontology are linked with the identifiers in the geometrical representation of the damage, thus only geometry formats with referable unique identifiers can be used for this application.

5. Application of Assessment Rules

In this section, rules for classifying and evaluating detected anomalies are described. Additionally, assumption rules are proposed for inferring undetected damages. Since these damages need to be proven as existent either through detection or system identification, they are labeled as uncertain, using the specific class *AssumedDamage*. For better clarification, simple examples are also presented, which refer to the degradation of an existing bridge. All rules are described in first-order logic in this paper.

5.1 Classification Rules

The detected anomalies in the ontology are either declared as a *Damage Element* or *Damage Area* with no further specification. Additionally, quantifications are assigned to each anomaly individual. Therefore, the various evaluation objectives need to be accomplished during the subsequent classification process. Initial classifications can already be made based on individual damage characteristics, which can lead to further inferences. Theoretically, this classification step can be skipped, however it simplifies the definition of resultant rules and enhances their comprehensibility due to the possibility to refer to the reasoned classes instead of certain properties. For instance, recorded cracks can be grouped into longitudinal, transverse or diagonal cracks based on their angle in relation to the affected component (see Equation 1 for example on diagonal crack).

$$\forall d \exists a \exists x \exists y (Crack(d) \land crackAngle(d,a) \land (a > x) \land (a < y) \rightarrow DiagonalCrack(d)) \quad (1)$$

However, the application of such a classification rule needs exact definitions that determine at which value ranges the damage is assigned to the specific class. In Equation 1 no standard defines at which angle a crack can be classified as diagonal crack. In general, this classification is mainly based on human interpretation. Therefore, provisional value ranges (e.g. x = 30; y = 60) can be defined in order to test the developed rules. Furthermore, it could become difficult for humans to classify a damage according to these criteria if multiple damages are physically connected through a pattern and possess different properties, e.g. a crack pattern that starts as a vertical crack and then evolves into a diagonal or transverse crack. Therefore, it is important to subdivide these patterns into single damage elements.

Another fact, which is of interest for the construction maintenance is the causation of the detected damage. Therefore, domain specific rules can be applied, which are mostly based on common expert knowledge. As an example, reasoning the settlement of fresh concrete as a causation for identified cracks is shown in Equation 2.

$$\forall d \exists co \exists cc \exists x \exists y (LongitudinalCrack(d) \wedge \mathrm{hasConcreteCover(co, cc)} \wedge \mathrm{crackDepth(d, x)} \wedge (\mathrm{x} < \mathrm{cc}) \wedge \mathrm{crackWidth(d, y)} \wedge (0.5 < \mathrm{y} < 2) \rightarrow SettlementCrack(d)) \tag{2}$$

Based on a previous classification regarding the crack angle, a longitudinal crack is identified. Alternatively, the value range of the measured angle can be asserted, which is more suited towards a machine-based damage detection. In addition, the width and crack are checked that must be in a certain value range, whereby the depth must not exceed the thickness of the concrete cover. If all three criteria are fulfilled the crack can be identified as a crack caused due to concrete settlement. Consequently, a new class is assigned to the damage, which indicates the causation. As an alternative, the causation can be defined via a string-based data property. One important fact that needs to be reasoned is whether an anomaly has an impact on the structural capacity and therefore is classified as structural damage or defect. This depends often on the type of damage and on the affected component. Furthermore, damages must at least affect one load-bearing component (not accounting traffic loads) in order to be classified as structural damage, so damages on non-load bearing components e.g. bridge caps or railings are considered defects (see Equation 3).

$$\forall d \exists co (Damage(d) \wedge hasDamage(c, d) \wedge \neg hasLoads(c) \rightarrow Defect(d)) \tag{3}$$

A rule for classifying a structural damage is shown in Equation 4. It should be mentioned that these rules are only valid for a certain type of components, in this case for a roller bearing of a bridge.

$$\forall d \exists co (LongitudinalCrack(d) \wedge \mathrm{RollerBearing(co)} \wedge hasDamage(co, d) \rightarrow StructuralDamage(d)) \tag{4}$$

Similar to Equation 2, an anomaly has been previously identified as longitudinal crack related to the affected component. Since the crack through the roller bearing has a serious impact on the movement and load bearing capacity of the support element the damage is classified as structural damage. However, the same is not necessarily true if another component is damaged by a longitudinal crack, thus the structural assessment requires always both, a classified damage and the affected component.

5.2 Evaluation Rules

When classifying a damage, it is always possible to infer certain parameters that have an effect on the construction. In most maintenance processes the important domains for assessment are the structural capacity, durability and safety. According to (BVBS, 2007) for each domain a factor can be assigned by the inspecting expert, which is based on similar classifications, described in the previous section 5.2. Therefore, these factors can be reasoned by utilizing rules as shown in Equation 5.

$$\forall d \exists co (GapingJoint(d) \wedge \mathrm{ElastomericBearing(co)} \wedge hasDamage(co, d) \rightarrow sFactor(d, 2) \tag{5}$$

In the example, an elastomeric bearing is affected by a gaping joint, which has an impact on the structural capacity. Thus, the related factor is assigned the grade 2. Similar to this, factors for durability and traffic safety are assigned. Consequently, a rule-based classification according to current standards would be feasible. It should be mentioned that common bridge inspection standards often define much more criteria for evaluating grades. More accurate methods for damage assessment, e.g. prognosis of the degradation process or traffic simulations require a greater number of inferred parameters. Despite of its importance, this research neglects the durability and safety and focuses on the structural capacity and the related parameters that could be reasoned by classifying damages. Therefore, the aim of the damage classification is the preparation of mapping the damage information into a structural analysis model to process a system identification utilizing additional monitoring data that reflect the actual construction behavior. Multiple approaches for modeling damages were considered such as the smeared or discrete crack approach (Bažant & Oh, 1983)(Cervenka & Saouma, 1995) as well as reducing the degrees of freedom or movement capacity of damaged support elements Therefore, an additional TBox has been developed, that is used for defining the corresponding mechanical parameters.

By utilizing evaluation rules, these mechanical parameters could be reasoned from specific damage types that affect certain components. Equation 6 shows an example, where a corroded area restricts the movement of a roller bearing.

$$\forall d \exists co \exists mx \exists my \exists mz \exists rx \exists ry \exists rz (HeavyCorrosion(d) \land RollerBearing(co) \rightarrow restrictedMovementX(co, mx) \land restrictedMovementY(co, my) \land restrictedMovementZ(co, mz) \land restrictedRotationX(co, rx) \land restrictedRotationY(co, ry) \land restrictedRotationZ(co, rz)) \quad (6)$$

In this case, the three movement and rotation degrees of a roller bearing are restricted if it is affected by heavy corrosion, which should be ideally modeled as a damage area. Therefore, specific reduction values could be assumed, however since the correct reduction is difficult to evaluate just by non-destructive inspection methods, it is recommended to variate these parameters and perform a system identification according to (Luu et al., 2018).

5.3 Assumption Rules

Despite a comprehensive inspection of the existing construction, often damages remain undetected, which cannot be identified with conventional non-destructive methods, e.g. broken reinforcing elements or cracks that are aggregated in the structure. By utilizing rules, these damages could be assumed based on previously detected damages and their context in the construction and its components. For instance, certain damages could be assumed, if a construction has been built in a specific time, where outdated standards were used. As an example, German bridges that were built before the age of 1972, have a higher risk of being damaged by stress corrosion cracking, due to different standards in dimensioning, e.g. the minimum reinforcement or a different traffic load assumption (Maurer et al., 2012) (see Equation 7).

$$\forall b \exists x \exists d (Bridge(b) \land ConstructionDate(b, x) \land (x < 1972) \rightarrow AssumedSCCDamage(d) \land hasDamage(b, d) \land probabilityFactor(d, 2) \quad (7)$$

When identifying, that the refurbishment of an inspected bridge is dated before 1972, a new damage individual is created as an instance of an assumed damage. In addition, the new individual is assigned to the construction and a probability factor is defined, which represents the occurrence probability of the assumed damage. Since at the time of this publication no studies existed regarding the calculation of these probabilities, instead of a percentage probability, an integer factor is used representatively. In addition to the construction properties, the aggregated components can also influence the damage progression, as shown in Equation 8.

$$\forall b \exists ps \exists x \exists d (Bridge(b) \land hasPrestressingSteel(b, ps) \land SteelType(ps, \text{"St 145/160"}) \land crosssectionType(ps, round) \land manufacturer(ps, \text{"Sigma"}) \land productionDate(ps, x) \land (x < 1965) \rightarrow AssumedSCCDamage(d) \land hasDamage(b, d) \land probabilityFactor(d, 10) \quad (8)$$

In this example, the prestressing steel of the bridge is defined as a product dated before 1965 from a specific manufacturer. According to (BAW, 2006), bridges that contain this type of prestressing steel in their structure, have a significant higher probability of stress corrosion cracking.

In the subsequent system variation and identification, the probability factors are configurable, so that it is possible to exclude low probabilities of certain damage types in order to decrease the amount of variations and thus increase the mass simulation performance. Therefore, for every assumed damage type, the sum of probability factors is formed. This can be achieved by processing a simple SPARQL Query as shown in Listing 1.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX asmptn: <http://www.wisib.de/ontology/damage/dotasmptn#>

SELECT (SUM(?probability) AS ?totalProbability)
WHERE {
        ?assumedDamage rdf:type asmptn:AssumedSCCDamage.
        ?assumedDamage asmptn:probabilityFactor ?probability.
        FILTER (?probability < 4)
}
```

Listing 1 SPARQL Query for determining the total probability of all assumed stress corrosion cracks with probability value less than four.

6. Conclusions and Future Work

Based on quantifications of detected anomalies, which can be either recorded manually by human experts or by machines, a web ontology could be produced which forms a knowledge database for subsequent information processing together with a linked web ontology of the existing construction.

By applying semantic rules, an initial classification can be processed, whereby additional properties can be inferred through the rule-based assessment of the damages. Furthermore, assumption rules can be applied to reason for undetected damages to be known from past projects. However, these damages can at most be classified as "Assumed Damages", since their existence need to be proven either by conventional measurement methods or simulation-based system identification approaches, which should be preferred in the context of non-destructive inspections. In processing a system identification, the mechanical parameters of the detected damages are variated and based on the results of the numerical simulation in context with monitored data of the construction. Assumed damages can be concluded and mapped on the structural analysis model for further simulations in an iterative process.

Initial Rules have been prototypically applied on an ontology, which represents an existing bridge construction. Nonetheless, a comprehensive validation of the method is still subject of future research. Furthermore, the generation of variations and their corresponding management needs to be developed for processing a system identification using the assumed damages. Consequently, the approach needs to be validated through the comparison with alternative methods, such as case-based reasoning, convolutional neural networks or frequency resonance method.

Acknowledgements

This research work was enabled by the support of the Federal Ministry of Education and Research of Germany through the funding of the project wiSIB (project number 01-S16031C).

References

BAW. (2006). *BAW Letter Nr. 3 (in German).*

Bažant, Z. P., & Oh, B. H. (1983). Crack band theory for fracture of concrete. *Matériaux et Constructions*, *16*(3), 155–177. https://doi.org/10.1007/BF02486267

Brecher, V. H., Paul B.-L, C., Hall, R. W., Parisi, D. M., Rao, R., Riley, S. L., & Sturzenbecker, M. C. (1996). *Patent No. US5544256A.*

BVBS. (2007). *Building inspection according to DIN 1076 (in German, original title: Bauwerksprüfung nach DIN 1076).* Retrieved from www.bmvbs.de

Cacciotti, R., Blaško, M., & Valach, J. (2015). A diagnostic ontological model for damages to historical constructions. *Journal of Cultural Heritage*, *16*, 40–48. https://doi.org/10.1016/j.culher.2014.02.002

Cervenka, J., & Saouma, V. E. (1995). Discrete Crack Modeling in Concrete Structures. *Fracture Mechanics of Concrete Structures*, 1285–1300.

Hamdan, A, & Scherer, R. J. (2018). *A generic model for the digitalization of structural damage*. IALCCE 2018, 2549–2556, Ghent, Belgium.

Hamdan, Al-hakam, Bonduel, M., & Scherer, R. J. (2019). An ontological model for the representation of damage to constructions. *7th Linked Data in Architecture and Construction Workshop*.

Huang, Z., Fu, H., Chen, W., Zhang, J., & Huang, H. (2018). Damage detection and quantitative analysis of shield tunnel structure. *Automation in Construction*, *94*(February), 303–316. https://doi.org/10.1016/j.autcon.2018.07.006

Lee, D. Y., Chi, H. lin, Wang, J., Wang, X., & Park, C. S. (2016). A linked data system framework for sharing construction defect information using ontologies and BIM environments. *Automation in Construction*, *68*(May), 102–113. https://doi.org/10.1016/j.autcon.2016.05.003

Li, G., Zhao, X., Du, K., Ru, F., & Zhang, Y. (2017). Recognition and evaluation of bridge cracks with modified active contour model and greedy search-based support vector machine. *Automation in Construction*, *78*, 51–61. https://doi.org/10.1016/j.autcon.2017.01.019

Luu, N. T., Hamdan, A., Polter, M., Scherer, R. J., & Mansperger, T. (2018). *A Variation Model Method for Real Time System Identification In Bridge Health Monitoring*. 1–7. Proc. IABSE 2018, Copenhagen, Denmark

Maurer, R., Heeke, G., Kiziltan, H., Kolodziejczyk, A., Zilch, K., Dunkelberg, D., & Fitik, B. (2012). *Nachrechnung von Betonbrücken zur Bewertung der Tragfähigkeit bestehender Bauwerke*. Bundesanstalt für Straßenwesen.

Morgenthal, G., Hallermann, N., Kersten, J., Taraben, J., Debus, P., Helmrich, M., & Rodehorst, V. (2019). Framework for automated UAS-based structural condition assessment of bridges. *Automation in Construction*, *97*, 77–95. https://doi.org/10.1016/j.autcon.2018.10.006

Pauwels, P. (2017). *Product and 3D geometry ontologies at action in construction industry : from manufacturer to demolition.*

Polter, M., & Scherer, R. J. (2018). Towards the application of the BIMgrid framework for aged bridge behavior identification. *EWork and EBusiness in Architecture, Engineering and Construction*, 163–168. https://doi.org/10.1201/9780429506215-21

Rasmussen, M. H., Pauwels, P., Hviid, C. A., & Karlshøj, J. (2017). Proposing a Central AEC Ontology That Allows for Domain Specific Extensions. *Lean and Computing in Construction Congress -*

Volume 1: Proceedings of the Joint Conference on Computing in Construction, (July), 237–244. https://doi.org/10.24928/JC3-2017/0153

Ren, G., Ding, R., & Li, H. (2019). Building an ontological knowledgebase for bridge maintenance. *Advances in Engineering Software*, *130*(July 2018), 24–40. https://doi.org/10.1016/j.advengsoft.2019.02.001

Scherer, R. J., & Katranuschkov, P. (2018). BIMification: How to create and use BIM for retrofitting. *Advanced Engineering Informatics*, *38*, 54–66. https://doi.org/10.1016/j.aei.2018.05.007

Shaya, E. (n.d.). Ontology: geometry. Retrieved May 8, 2019, from https://www.astro.umd.edu/~eshaya/astro-onto/ontologies/geometry.html

Xu, Z., Li, S., Li, H., & Li, Q. (2018). Modeling and problem solving of building defects using point clouds and enhanced case-based reasoning. *Automation in Construction*, *96*(February), 40–54. https://doi.org/10.1016/j.autcon.2018.09.003

BIM-enabled “Digital by Default” Vision for Fire Safety

Dr. Kirti Ruikar[1*], Dr Peter Wilkinson[2] and Judith Schulz[3]
[1]Loughborough University
[2]Pyrology Limited
[3]Arup
* email: k.d.ruikar@lboro.ac.uk

Abstract

In England and Wales, building regulations apply to the design and construction of new buildings, extensions and changes of use. Regulation 38 (BRE, 2019) is a requirement to provide fire safety information to the responsible person at the completion of a project, or where the building or extension is first occupied. Regulations require as-built Fire Safety Information to be handed over by the design and construction teams to the responsible person to maintain and operate a building with reasonable safety. The responsible person is the owner, occupier, or manager of the building. The information would typically include; a fire safety strategy of the building that accurately reflects the fire safety precautions; and design and construction information, services information; and information about fixtures, fittings and equipment. Unfortunately, Regulation 38 has been far from successful and the required information is rarely communicated to the dutyholders in a manner that meets the intention of the authors. There is no requirement for the information to be presented to either the Fire Service or the Building Control Body for assessment. The requirement is merely for the person carrying out the work to confirm that the required information has been passed over (CIC, 2017). The guiding philosophy of legislation requires organisations to assess the potential risks associated with their work activities and to introduce effective measures to control risks. However, in reality the current regulations set the bar too low, with the industry looking to satisfy the minimum standards by the cheapest means possible, magnified by a lack of approval scrutiny.

In the wake of the Grenfell Tower fire in 2017 that killed 72 people, the UK Government commissioned the Hackitt Review (2018) of building regulations and fire safety. The Hackitt Review calls for radical change in culture in the construction industry and the regulatory system that assigns responsibility and holds people accountable. It also states that the Government should mandate a digital standard of record-keeping for design, construction and occupation of new Higher Risk Residential Buildings (HRRB) and refurbishments within HRRBs. A BIM-driven dataset is suggested, which requires duty-holders to generate a suitable evidence-base through which to deliver their responsibilities and maintain safety and integrity throughout the lifecycle of a building. This paper will examine the requirements set out in the Hackitt review and explores the need for a digital record of lifecycle building information. It examines examine the role of BIM as an enabler of the digital building information record and presents a conceptual framework that enables rapid realisation of the digital by default vision, via a Safe by Default Asset Delivery framework. It outlines the potential outcomes of the safe by default approach and discusses the potential opportunities and challenges likely to be considered if the BIM enabled “digital by default" vision was to be realised.

Keywords: Fire Safety, BIM, Hackitt Review, Safe by Default

.

1. Background

Fire safety within the built environment has been a subject of concern for thousands of years (Wilkinson, 2013). In the 20th century, experiences from fires during the second world war were incorporated into the Post-war Building Studies on Fire Grading of Buildings (Wilkinson et al, 2010) and these were landmark documents of their time (Malhotra 1987 in Wilkinson et al 2010) that influenced the technical content of subsequent Building Regulations. Before amendments were made in 1976, regulations were highly prescriptive (Wilkinson et al 2010) and criticised to be "understood only by lawyers" (Law, 1991 in Wilkinson et al 2010). Despite the criticism, prescriptive Building Regulations resulted in the achievement of safety levels within buildings that were largely accepted by the community (Hasofer et al in 2007 in Wilkinson et al 2010). The events of the Grenfell fire, however, shook public confidence and 2017/18 also saw a 27% increase in fire related fatalities as a result of the tragic events of the Grenfell fire. In 2017/18, of the primary fires (74,118 fires) attended by the Fire and Rescue Services (FRS) in 2017/18, 63% were in dwellings and other buildings. The remaining were road vehicle and outdoor fires. The Grenfell tragedy and several before it, point to systemic failures, some of which can be attributed to 'piece meal approaches' to design development and construction, lacking holistic consideration, unsafe building components and material choices, failures in keeping maintenance audits of safety work, major or minor buildings works, all of which adversely impact on the integrity of the building structure and its fabric and result in a compromised safety function. The fire statistics (Home Office, 2018) and systemic failures call for radical improvements in practice so that mistakes are not repeated, and lessons are learnt. In the "Building a Safer Future" review by Dame Judith Hackitt (2018), there are several recommendations calling for radical changes in practice. Discussed in this paper are the recommendations to mandate a digital standard for record-keeping of through-lifecycle, design, construction and occupation information. This applies to Higher Risk Residential Buildings and refurbishments within those buildings and requires duty-holders to generate an evidence-base through which to deliver their responsibilities and maintain safety and integrity throughout the life-cycle of a building. The Hackitt review identifies a "Golden Thread of Building Information", to comprise of a digital record and a Fire and Emergency File (FEF). The review recommends that the client, principal designer and contractor maintain the FEF. The FEF to include technical specifications, product information, O&M manuals and inspection/commissioning records. More specifically, the Hackitt outlines the contents of such a FEF to include:

- A copy of the fire strategy design report for the building which details the strategic measures that are provided in the building to satisfy Parts B1-B5 of Schedule 1 of the Building Regulations (HM Government, 2010) (for which compliance related guidance is provided in Approved Document B); and
- For each Parts B1-B5 the FEF should include:
    - All relevant technical specifications
    - Product datasheets
    - Operations and maintenance manuals
    - Inspection and commissioning records

A BIM-driven (Building Information Modelling) dataset has been recommended for the digital record and the FEF. The next section will examine the requirements set out in the Hackitt review and explore the need for a digital record of lifecycle building information.

2. Hackitt Review and the Need for a Digital Record of Lifecycle Building Information

Currently, the precise extent of the as-built fire safety information and the level of detail that is provided to the owner or occupier varies and is dependent on the complexity of the building's design, its function and its susceptibility to a fire. The typical design considerations include: provision of passive fire protection measures designed to control fire spread, limit the effects of fire, protect escape routes and prevent structural collapse; inclusion of active detection and alarm systems to alert occupants to elicit a rapid response; use of smoke control systems to limit smoke spread; and provision of fixed firefighting systems to detect and extinguish fires or at least control their spread. The precise extent of as-built fire safety information and the level of detail that is provided to the owner or occupier varies and is dependent on the complexity of the building's design, its function and its susceptibility to a fire. According to Dobson (2018), *"Our current regulatory, testing and compliance regime has produced a complex ecosystem of contradictory guidance and conflicted interests, and in the process, we seem to have lost sight of the basics of fire-safe design." "While fire engineering on high-specification, high-budget projects with experienced client bodies can support innovation in design, on more typical projects it is too often a method of subverting core principles that have been developed over generations since the Great Fire of London."* The current regulations set the bar too low, with the construction industry looking to satisfy those minimum standards by the cheapest means possible (Timson in Brister, 2013), compounded by a lack of approval scrutiny (Ruikar and Glockling, 2015). This coupled with the, complete lack of application of fire regulation requirements results in incomplete, inadequate or sub-standard fire-safety information being handed over to the owner or occupier of a building. Such adversarial practices continue to put buildings at risk. Post-occupancy Fire Risk Assessments (FRAs) routinely reveal a variety of operational, maintenance, design and construction-related defects that present risks to the building's occupants; and negatively impact on the building's resilience to fires (Ruikar, 2018). This problem is compounded by the fact that several stakeholders are responsible for creating and maintaining building information, whose collective inputs affect the safety objectives. Generally, the stakeholders who are responsible for generating the information (designers, engineers, manufacturers) are different from those responsible for maintaining the asset (owners, occupiers, facilities managers) and/or those responsible for protecting it (fire and rescue services). In an emergency, the fire and rescue services are required to make snap decisions with the information at hand and often the effectiveness of the decision is based on the availability, correctness, and/or the completeness of the information available to them.

In the wake of the Grenfell tragedy, the Hackitt Review (2018) called for a digital record of building information to be maintained through lifecycle. The intent being to preserve a digitally driven dossier of building information that holds up-to-date and accurate information in a secure and accessible environment. Such a digital record would enable duty-holders to deliver their responsibilities and maintain safety and integrity throughout. BIM tools provide an environment in which the digital record could be maintained. It is envisioned (Hackitt Review, 2018) that a BIM-driven dataset would ensure decision-making is based on robust data, quality and compliance is assured, and efficiency is achieved through collaboration and innovation.

To create a digital record would require gathering the information requirements that are critical to various stakeholders at different stages of the building lifecycle i.e. design, manufacture, construction and operations. This is an under-researched and under-explored area of work. To truly automate the information cycle, it is critical to ensure that essential safety information is engrained in the building lifecycle process. To achieve an automated outcome, how the 'intelligent' process and product data (e.g. product specifications, properties, product life) could be input into BIM would need to be firstly established. Then, operational safety performance data of the product, extracted from BMSs and IoTs could be linked to the intelligent process and product data within BIM to validate and/or update 'operational' fire safety information.

3. BIM as an Enabler of the Digital Building Record

BIM has been mandated in the UK since 2011 (Cabinet Office, 2011). It has been defined by the HM Government BIM Task Group (2016) as, "value creating collaboration through the entire life-cycle of an asset, underpinned by the creation, collation and exchange of shared 3D models and intelligent, structured data attached to them". The UK Government's BIM hypothesis has been that the Government as a client can drive significant improvements in cost, value and carbon performance using open sharable asset information. For instance, the UK Government's construction 2025 (HM Government, 2013) targets, among other targets for the construction industry, have been to drive down costs by 33% and increase project delivery times by 50% for new builds and refurbishment projects. These are ambitious targets that cannot be met without a radical overhaul in current practices. The UK spends approximately £90 billion on Capital Expenditure of built assets each year. Of the total assets, approximately half are public assets. In comparison Operational Expenditure is £122 billion each year. Thus, the Government's urge has been for the industry to explore new ways of being effective. This drive from the Government for the industry to improve isn't new. Historically, there have been several Government reports (see timeline in Figure 1) starting with Sir Michael Latham's report on "Constructing the Team" in 1994 (Latham, 1994) which urged the industry to enhance teamwork and address the adversarial practices that affected its image. Subsequent reports such as "Rethinking Construction" (Egan, 1998), Accelerating Change (Egan, 2002), Never Waste a Good Crisis (Wolstenholme et al, 2009), Government Construction Strategy (Cabinet Office, 2011) and Government Construction Strategy 2016-2020 (2016) all call, among other things, for the industry to improve performance, accelerate change, enhance teamwork, work collaboratively, explore new ways of working, embrace technology and more recently use BIM.

Figure 1: Historic TimeLine of Influential UK Construction Industry Government Reports

There are several BIM standards that provide a framework for information management through-lifecycle. Examples include the BS EN ISO 19650 series (ISO 19650-1 and ISO 19650-2) (BSI, 2019) of international standards for managing information over the lifecycle of a built asset using BIM. These are founded on UK standards for information management using BIM. The Hackitt review calls for a through-lifecycle digital record of asset information to be maintained and made available to the duty-holders to perform their duties and maintain a facility. BIM is an enabler of the digital record. A typical BIM, depending on the level of maturity, would hold information about the asset generated by different stakeholders, including architects, structural engineers, fabricators, building services engineers and bridging engineers. The BIM would hold contextual information about the objects (e.g. building components) contained within the model. Typically, this would include information such as product (or object) data (Eastman et al, 2011; Emmitt and Ruikar, 2013) product specifications, properties (physical attributes, geometries, chemical composition) (Eastman et al, 2011; Emmitt and Ruikar, 2013) and other user-defined attributes such as performance characteristics, costs and fire ratings, combustion properties and ignition properties, as examples.

PAS 1192-3, now superseded by ISO 19650 (HM Government, 2007), provides a framework for information management at the operational phase. It requires the duty-holders to capture information in the asset information model, at various "trigger" points when the information about the asset is likely to change. Changes to be recorded are those due to minor works, major works, refurbishments, maintenance, end-of-life and other similar triggers, which affect the integrity of the asset information. Thus, a BIM environment provides a means to generate up-to-date, asset lifecycle information, as is recommended by the Hackitt Review. The creation of an up-to-date asset information model that holds critical information about fire safety is very important, as it forms an integral part of the digital record and the FEF to be handed over to the Fire and Rescue Services, in the event of an emergency. The effectiveness of a timely response would be dependent on the completeness of the information that preserves the design intent and maintains the asset's history in the FEF. Providing access to up-to-date building information to owners and/or duty-holders is thus, critical for effectively carrying out FRAs (fire risk assessments) and taking remedial actions to mitigate potential risks and ensure occupant safety. This digital replica of the as-built physical asset which models related product and process data is a 'digital twin'. This concept is not new and has had its roots in the Aerospace industry. It has grown in prominence in the UK construction literature (Savian, 2019; and Fryer, 2019; Madni et al, 2019) due to the digital drive in the construction industry. For instance, according to Fryer (2019), modelling products and processes has been around for a few decades, but recently we have seen an emergence of digital twins (Ross, 2019), which have their origins in the design process. Over the years this has transformed design and manufacturing due to the creation of repeatable and reusable automated processes to predict and optimise performance and to realise the fully automated potential. These changes would need to be supported by developing digital workflows. Such a digital twin would fulfil the digital record related requirements outlined in the Hackitt Review, which recommends that the FEF should be a clearer obligation on the client, Principal Designer and Principal Contractor to initiate, update and finalise and then pass onto building owner to help them to better understand how a building management is improved in the event of a fire. The review includes a non-exhaustive example list of the type of information to be recorded, maintained and made available to the duty holders, as follows:

- Size and height of the building
- Full material and manufacturer product information
- Identification of all safety critical layers of protection
- Design intent and construction methodology
- Escape and fire compartmentation
- Records of inspections/reviews/consultations
- Building structure and fabric
- Permanent fixtures and fittings

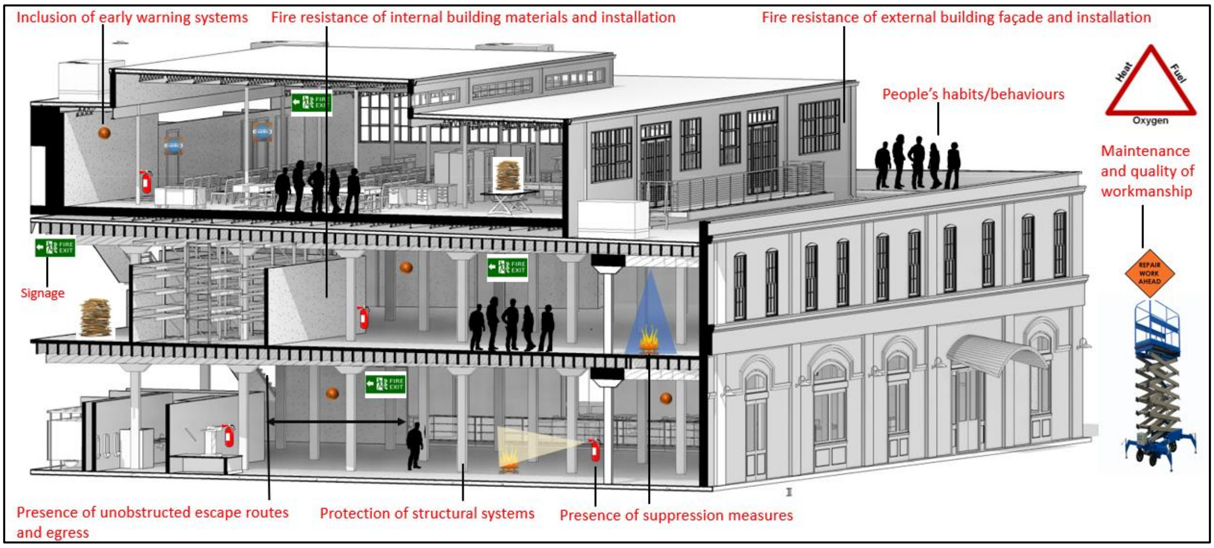


Figure 2: Fire engineering and safety information to be recorded in a BIM

It is widely recognised that several, 'disparate' stakeholders are responsible for creating and maintaining building information, whose collective inputs affect the fire safety objectives. Often the stakeholders who are responsible for generating the information (e.g. designers, engineers) are different from those constructing the building (e.g. contractors, sub-contractors) and from those responsible for maintaining the building (e.g. owners, occupiers, facilities managers) and/or those responsible for protecting it (e.g. fire and rescue services). In an emergency, the fire and rescue services are required to make snap decisions with the information at hand and often the effectiveness of the decision is based on the availability, correctness, and/or the completeness of the information available at hand. Thus, any future digital FEF would need to ensure that the needs of those responsible for safeguarding the interests of the asset are engaged in critical stages of the design and development processes so the information that is collected is of use to them in an emergency. Because, in a typical project, there are different stages and different stakeholders involved, each with their own set of information requirements, it is critical that each stakeholder group is represented at the requirements capture stage, so their needs are appropriately met. For this purpose, an approach to design 'digitally' with the end in mind is adopted so that the resultant asset is safe by default.

4. Proposed Conceptual Framework for a Safe by Default Asset Delivery

The Hackitt review recognises the potential risks to occupants and visitors of buildings in emergency situations and recommends that "relevant professional bodies" can help determine the scope of information to be included in the FEF. Representation from the relevant bodies would ensure that their requirements, from a fire safety perspective, are met. These bodies represent disparate stakeholder groups, each of which are involved at different stages of the project. In a typical project, project teams form, disband and (sometimes) reform at different lifecycle stages. Throughout the lifecycle of the process these teams use discrete software systems to process documents, graphical and non-graphical building information. This information could be potentially lost, if not captured in context. To mitigate the risk of knowledge loss and to control its adversarial impact on the project's safety objectives, it is critical that the digital record and the FEF are contained within a 'digitally tracked' process that progressively records the information as the project progresses. Also, from a fire safety objective perspective, there is an underlying need to capture the information within context and structure it such that the information requirements of the stakeholders (to meet fire safety objectives) are firstly understood and then met. For this purpose, the "safe by default" conceptual framework has been developed with the collective stakeholder perspective in mind. It recognises that the collective inputs of interdisciplinary stakeholders affect lifecycle fire safety objectives and subsequent safety outcomes. Because, those responsible for generating the information (e.g. designers, engineers), are different from those who maintain the building (owners, occupiers, facilities managers) and those who protect it (Fire and Rescue Services), a digital approach to designing with the end in mind and ensuring lifecycle safety objectives are met from the start, is proposed. The conceptual framework thus, encourages interdisciplinary stakeholder representation at different lifecycle stages of a building, so their requirements are met. The inter-disciplinary engagement promotes a joint-up, interdisciplinary approach to problem-solving to understand 'holistic fire-safety' information requirements, facilitate information capture and process, validate and disseminate information beyond what is currently possible. Safe by default framework (Figure 3) promotes a BIM-enabled, cross-sector stakeholder-driven best practice approach to capture and maintain contents of a digital FEF at key lifecycle stages (RIBA 0-7).

4.1 Safe by Default Approach Using a Participatory Workshop Method

The research proposes a participatory workshop method to actively encourage people to participate in workshop activities, instead of being passive recipients in the research inquiry process. Thus, rather than passively receiving information from outside experts, who may not have local understanding of the issues (e.g. concerning an emergency response, fire-engineering in design, maintaining FEFs), participants are encouraged to share information, learn from each other, and work together to solve common problems (Newman, 2019). This method relies on active participation from workshop stakeholders, who are intrinsic to the 'problem' of study. The sample size can have a considerable effect on the quality of qualitative research (Coyne, 1997). An adequate sample is that in which the breadth and depth of information has been achieved (O'Reilly and Parker, 2012 in Zanni, 2016). Through enabling an inter-disciplinary dialogue that brings together cross-disciplinary stakeholders with representation (i.e. *sample*) from the various stages of the lifecycle process, the key areas of inquiry in relation to fire-safety and BIM could be determined. This would accelerate the emergency response and ensure that the response is based on *"readily available digital building information that is accurate, updated, complete and accessible".* The approach enables rapid realisation of the requirements of the Hackitt Review (2018). For this, an approach that promotes a series of workshops at critical stages of the project process is proposed. Each workshop [W1-3] will enable identification of the information needs to be captured in the digital record, [WI] before occupying the building (during design and construction); [W2] during occupation (post-handover and in-use); and [W3] in an emergency to protect the building. This would ensure that the golden thread of information, as recommended by the Hackitt Review, persists throughout the building's lifecycle, and thus, delivers a digitally-tracked twin.

The safe by default approach will enable gathering and developing the information requirements that are critical at different stages of the building lifecycle i.e. design, regulatory approval, manufacture, construction and operations. This is an under-researched and under-explored area of work. It is critical to ensure that essential safety information is embedded from the design stage onwards, to inform manufactured components used in construction, to be carried through so it is available to the end users, preferably in an automated fashion. To achieve the aspiration of 'safe by default' through automatic validation and updating of product and strategic data within BIMs at different lifecycle stages of an asset will require knowledge capture from various stakeholders and connecting it to the BIM. For this purpose, cross disciplinary workshops will be conducted, they will include stakeholder representation from designers, fire safety experts, fire and rescue services, building component manufactures, safety systems manufacturers, health and safety experts, regulatory bodies with duties to approve plans and enforce fire safety matters, technology solution providers, building insurers and building owners.

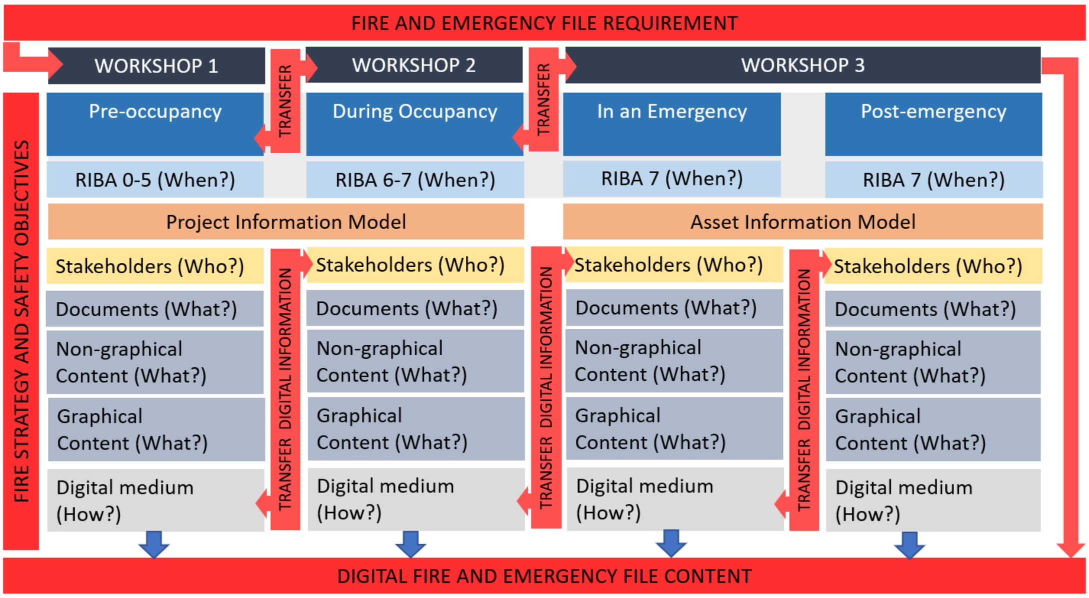


Figure 3: Safe by Default Conceptual Framework

For this it would be essential to initiate and grow a cross-industry interest group (CSSIG) with a focus on fire safety information needs of end-users, to fill a gap in policy and provide guidance on how fire safety is properly considered in BIM that does not exist currently. This will ensure public safety and quick emergency response are at the heart of the digital transformation that the construction industry is currently undergoing. The novelty of the proposed approach lies in connecting currently 'disparate' cross-disciplinary stakeholders, whose collective actions affect the 'safe by default' aspirations. Doing so, would enable the special interest group to work alongside technology providers to achieve a common goal of identifying the ingredients of the 'golden thread of building information' and the delivery of digitally tracked twin, by leveraging current and emergent technologies and their requirements for information capture and validation, so safety is by default and design is with the end in mind. This research group will also be able to identify the information and skills gaps that are apparent within the current construction supply chain and those that are required to be developed to achieve this safe by default vision. For example, embedding safety information within manufactured components and then allowing automated verification and relaying of the information to BIM is one of the key challenges' manufacturers face in both, technology and workforce skills development. Identifying these skills gaps and upskilling the supply chain is a requirement and in line with the expectations of the Industrial Strategy Construction Sector Deal. This could revolutionise the way in which UK designs, constructs and operates buildings and infrastructure by realising the potential to integrate advanced construction product manufacturing with state-of-the-art digital design, for a safe and resilient outcome.

4.2 Workshops and Outputs

Digital stakeholder requirements would be captured through three stakeholder workshops [W1-3] representing different lifecycle stages (see Figure 3). The proposed workshops would engage construction's academic and industrial communities and connect them with those communities that are responsible for safe-guarding the interests of the public in delivering the 'safe by default' asset in the event of a fire-related emergency.

The Government's soft landings guidance recommends that the building's 'in-use' or 'operations' phase should be considered throughout the project's lifecycle- from cradle to grave. Given that BIM has been mandated for publicly procured buildings (Cabinet Office, 2011), the clients are increasingly acquiring information in digital forms. The information exists in documents and in graphical and non-graphical formats. As the amount of information progressively increases in complexity, level of detail and changes formats from the early design, through construction and to the in-use phases of the project, so does the need to effectively manage the information become critical, particularly so that the safety objectives are met. Also, the information is collectively generated by a range of stakeholders, whose participation at the requirements capture stages is critical for the quality and completeness of the information generated. The typical stakeholders who would participate in the workshops would include representatives from (but not limited to): Clients, Representatives from Local Council, Designers (architects, structural), Manufacturers, Product suppliers, BIM managers, Technology tool providers, Contractors and sub-contractors, Fire Engineers, Fire and rescue services, Occupants (Duty-holders), Facilities Managers of High Risk Highrise Buildings, Academics, Government and Policy-makers.

To ensure that the golden thread of building information is captured using BIM as a vehicle, the safe by default approach would, through a series of workshops, capture:

- [W1] Project Information Model (PIM) requirements at the pre-occupancy stage of a project to represent RIBA 0-5;
- [W2] PIM requirements during-occupancy stage of a project to represent RIBA 6-7; and
- [W3] Asset Information Model (AIM) requirements of response teams in-an-emergency and post-emergency to represent RIBA 7.

With reference to the fire strategy and the intended fire-safety objectives, each of the above information requirements [from W1-3] would be categorised into templates [T1-3] that capture the digital information about:

1) Who is responsible? Stakeholder/s responsible for creating, organising, storing, sharing and (re)using the fire-safety information.
2) What is the information? Identifying documents, standards, graphical and non-graphical contents created, organised, stored, shared and (re)used at different stages of the RIBA (0-7) lifecycle. Here consideration would be given to capturing the content at "triggers" identified in the AIM (BS EN ISO 19650)8, when the information is likely to change.
3) How the information will be created, organised, stored, shared and (re)used? Identifying digital tools that are used to create, store, share and (re)use the digital record. Consideration would be given to the longevity of the information, so that it is migrated to systems that are current (i.e. not obsolete).

Templates [T1-3] would be created to identify specifics of the Who? What? When? and How? of the information-cycle at RIBA stages. The 'why', i.e. designing with the 'end in mind' for a safe by default outcome, would form the thread that connects the three workshops and their outputs. [W1-3]. Each template, starting with T1 (through T2 towards T3) will capture digital information requirements of the corresponding stage (i.e. pre-occupancy, during-occupancy and in-an-emergency/post-emergency). This information would be transferred iteratively between stages to refine the template content, so that progressively 'developed' information continues to be captured in context and remains up-to-date. Iterations ascertain that the digital record tracks changes so that the contextual ('fire-safety') characteristics of the physical DNA are identified (and represented) in the DNA of the digital twin.

4.3 Opportunities

The proposed conceptual framework presents opportunities that enable:

- Mapping of the various documents generated through the lifecycle of a building project, within which decisions affecting a building's fire safety objectives (e.g. fire strategy design report) are contained, against the information management requirements identified in the operational phase of the asset using BIM (to fulfil BS EN ISO 19650).
- Agreement on and help with defining the roles and responsibilities of stakeholders to support knowledge processes as per the requirement to source, create, capture, share, transfer and re-use fire-safety knowledge (i.e. information in context).
- Developing a BIM-enabled stakeholder-driven best practice template for digital record keeping at critical stages of the project's lifecycle so digital records and contents of the FEF based on identified stakeholder requirements are captured and maintained at various 'trigger' points identified in the ISO 19650.

4.4 Challenges

Although there are several opportunities to be had from adopting the safe by default approach, the are challenges too, these are:

- Designing with the end in mind requires a radical shift in how projects would be delivered. This necessitates early engagement of stakeholders, who are currently involved much later in the process. For this to happen, new datasets and workflows would need to be defined;
- Defining new datasets and workflows for fire safety requirements in the BIM process would require cross-disciplinary stakeholder engagement at requirements capture stage. Identification of these stakeholders and acquiring buy-in from them would be essential;
- Early engagement of Fire and Rescue services to deliver 'requirement-specific' (in an emergency) BIM datasets and related digital workflows is critical, if this 'radical' vision is to be realised;
- Providing Fire and Rescue services with uninterrupted access to 'current' digital records (and the FEF) during an emergency would require secure access to data;
- Identifying gaps in existing skillsets of the supply-chain which limit the provision of digital records;
- Driving a top down push from Clients to propel ubiquitous adoption of BIM in the construction industry;
- Making sure that the information is available in an accessible format to the different stakeholders throughout the building's lifecycle;
- Ensuring that information storage formats/media are always current (not obsolete); and
- Safeguarding information security and ensuring the record is being regularly updated in the digitally tracked twin.

5. Summary and Conclusions

The paper presented a novel approach to deliver 'safety by default' so costly lessons could be avoided. The basic premise of the proposed conceptual framework has been to ensure that safety isn't an afterthought and designs are done with the 'end in mind' resulting in a building that was safe by default. With this guiding principle, the research, "Safe by Default" enables the rapid realisation of the Hackitt review recommendations by providing a framework that enables the capture and storage of digital building information affecting fire safety of buildings through lifecycle. The approach is built on the premise that BIM provides the backbone to hold critical fire safety building information and assists in creating a safety-enhanced digital twin of the physical asset. There are several opportunities for realising this ambition, but numerous challenges still remain.

References

BRE 2019, Regulation 38 and fire safety engineering. Available from :- http://www.bre.co.uk

Brister, A. (2013). [online]. In the Line of Fire. Modern Building Services. Published 04 April 2013. Available from: - http://modbs.co.uk Accessed (09/03/2015).

British Standards Institution, (2012) PD7974-8 Application of fire safety engineering principles to the design of buildings – Part 8: Property protection, mission continuity and resilience. London: BSI.

British Standards Institution, (2019) Transition guidance to BS EN ISO 19650. London: BSI.

BSI (2019) BS EN ISO 19650 1&2: 2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building information modelling. BSI.

Building Information Modelling (BIM) Task Group. 2016. Frequently asked questions. http://www.bimtaskgroup.org/bim-faqs/.

CIC (2017). Construction Industry Council. Submission of evidence to the Independent Review of Building Regulations and Fire Safety.

Coyne, I. (1997). Sampling in qualitative research. Purposeful and theoretical sampling; merging or clear boundaries? Journal of Advanced Nursing. Vol. 26 Issue 3, pp. 623-30 Available from :- https://www.ncbi.nlm.nih.gov/pubmed/9378886

Dimyadi, J. and Amor, R. (2018) BIM-based Compliance Audit Requirements for Building Consent Processing, Proceedings of EC-PPM 2018, Copenhagen, Denmark, 12-14 September, pp. 465-471

Dobson, A. (2018). [online]. We need minimum prescriptive requirements in building regulations. Inside Housing. Available from:- https://www.insidehousing.co.uk/comment/comment/we-need-minimum-prescriptive-requirements-in-building-regulations-55212 Accessed on: 07/05/2019

Egan, J. (1998). Rethinking construction. London: Department of Environment, Transport and the Region. Department of Environment, Transport and the Region. London

Egan, J. Sir (2002) Accelerating Change. Rethinking Construction, London.

Fryer, T. (2019). Industry benefits from the digital baby boom. Meet the New You, The rise of the digital twin- from products to people. Virtual Models in medicine, manufacturing, maintenance and more. Engineering and Technology, Volume 14, Issue 1, February 2019.

Government Construction Strategy 2016-2020. (2016). 1st ed. London: Infrastructure and Project Authorities, pp.2-8.

Hackitt, J Dame (2018) Building a Safer Future, Independent Review of Building Regulations and Fire Safety: Final Report.

Hasofer AM, Beck VR, Bennetts ID. (2007). Risk analysis in building fire safety engineering. Oxford: Butterworth-Heinemann, UK.

HM Government (2007). Approved document B. Fire safety. HM Government.

HM Government. (2013) Construction 2025. Industrial Strategy: government and industry in partnership. London.

Home Office (2018). National Statistics. Detailed analysis of fires attended by fire and rescue services, England, April 2017 to March 2018. Available from: https://www.gov.uk/government/statistics/detailed-analysis-of-fires-attended-by-fire-and-rescue-services-england-april-2017-to-march-2018 (Accessed: 09/05/2019).

Latham, M. Sir (1994). Constructing the team. London: HMSO.

Madni, A. M., Madni, C. C. and Lucero, S. D. (2019). Leveraging Digital Twin Technology in Model-Based Systems Engineering. Systems. Volume 7, Issue 1. Available from: - https://doi.org/10.3390/systems7010007 (Accessed 08/05/2019).

Malhotra, H.L., (1987). Fire safety in buildings. Borehamwood, Herts.: Building Research Establishment.

Newman, J, M. (2019). Participatory Workshops Understanding Participatory Approaches to Learning. Published by the International HIV/AIDS Alliance. Available from :- http://www.lupinworks.com/roche/workshops/1-understanding.php. (Accessed: July 2019).

Ross, D. (2019) Editor's Letter, Meet the New You, The rise of the digital twin- from products to people. Virtual Models in medicine, manufacturing, maintenance and more. Engineering and Technology, Volume 14, Issue 1, February 2019.

Ruikar, K and Glockling, J (2015) Dr Kirti Ruikar and Dr Jim Glockling explore whether a digitised owner's manual is the answer to future resilience and examine opportunities presented by Building Information Modelling to facilitate compliance with Regulation 38 of the Building Regulations, Fire Risk Management, (April), ISSN: 1757-1324

Ruikar, K. (2018). Building Information Modelling and Regulation 38; Using information systems for resilience. Workshop 1 Presentation. Fire Sector Summit. 10-11 November 2014. Sopwell House Hertfordshire. UK

Savian, C. (2019). Potential to use BIM data in digital twins is being overlooked'. BIM Plus. Available from :- http://www.bimplus.co.uk/analysis/potential-use-bim-data-digital-twins-being-overloo/

Wilkinson, P.J., Glockling, J.L.D, Bouchlaghem, N.M. and Ruikar, K.D. (2010a) Has fire engineering lived up to expectations? Proceedings: 8th International Conference on Performance-Based Codes and Fire Safety Design Methods, 16-18 June 2000, Lund University, Lund, Sweden. Bethesda, MD and Dept. of Fire Safety Engineering, Lund Universitet.

Wolstenholme, A., Austin, S., Bairstow, M., Blumenthal, A., Lorimer, J., McGuckin, S., Rhys Jones, S., Ward, D., Whysall, D., Le Grand, Z., Guthrie, W. and Richards, D. (2009). Never waste a good crisis: a review of progress since Rethinking Construction and thoughts for our future. London: Constructing Excellence.

Zanni, M. A. (2016). Communication of Sustainability Information and Assessment within BIM-enabled Collaborative Environments. Doctoral Thesis, Loughborough University.

Game technology and Building Information Modelling for the adoption of Virtual Reality in construction safety training: a prototype protocol

Vito Getuli[1*], Pietro Capone[1], Alessandro Bruttini[1]
[1]University of Florence – Department of Civil and Environmental Engineering, Florence, Italy
* email: vito.getuli@unifi.it

Abstract

Building construction is considered a complex, dynamic and highly hazardous process which embraces many factors that are potentially dangerous to workers. Many studies proved that the improvement of preventive and proactive measures -dynamically included in the building design, planning and construction- could reduce site accidents as well as increase the site productivity. In this context, process management models and information visualization techniques such as Building Information Modelling (BIM) and Virtual Reality (VR) seem to be devoted to strongly contribute to the advancement of the current safety management practices. For these reasons, the presented contribution is based on the assumption that a more nuanced approach for construction worker's safety training is warranted and the authors propose a safety training protocol based on BIM-enabled virtual reality activity simulations. The protocol addresses three methodological issues: (1) *Planning* in terms of training typologies and related Health and Safety contents to be implemented in the VR construction site scenarios; (2) *Management* regarding the solution to integrate BIM and game technologies to deliver VR training experiences; (3) *Administration* in terms of definition of standardized rules to define a safety training schedule in a given construction project. The research gives a contribution to reduce the currently existing knowledge gap regarding how BIM and VR can be simultaneously integrated in real projects for construction safety training by using standardized rules to be extensively reproduced in different construction projects.

Keywords: Immersive Virtual Reality, BIM, Safety Training, Game Technology

1. Introduction

Building construction is considered a complex, dynamic and highly hazardous process which embraces many factors that are potentially dangerous to workers. Many studies proved that the improvement of preventive and proactive measures -dynamically included in the building design, planning and construction- could reduce site accidents as well as increase site productivity. Nonetheless, construction industry remains one of the major high-risk industries world-wide (Behm, 2005; Niza et al., 2008). The accidents are mainly caused by falling from height, workspace collision, wrong space usage, collapse and electric shock, among which falling from height and collisions are the most prevalent (Sokas et al., 2009). Other causes come from non-compliance in the application of the Health and Safety Regulation (HS) (Activity Report CPT, 2017) in terms of: (1) extensive lack of warning signals for the identification risk zones, (2) lack of site personnel having specific safety tasks; (3) lack of education in terms of site planning and coordination; (4) shallow risk analysis inconsistent with the specific construction site.

Given these circumstances, there are still considerable safety problems in the construction industry in need of attention. In this respect, enhancing safety training has been identified as an important factor able to reduce the accident rates in the construction industry (Abdelhamid and Everett, 2000; Tam and Fung, 2011). This means that an efficient construction safety training programme which include standardized rules for planning, management and administration could improve safety performance through preventing accident occurrence.

Nowadays, the most flourishing technology in the construction sector is represented by Building Information Modeling (BIM) and BIM-enabled applications. This technology provides a new approach to design, construction, and facilities management, wherein a digital representation of the building process is used to facilitate the exchange and interoperability of information (Eastman et al., 2011)(Vito Getuli, Mastrolembo, Capone, & Ciribini, 2016). Currently, as reflected in the literature, there are many proposals that use BIM technology to assist with different construction management tasks as safety management. These studies demonstrate that the use of a 4D (3D + Schedule) Building Information Model can be used as an important information source for the implementation of safety protocols.

The study which is proposed in this contribution is based on the assumption that a more nuanced approach for construction worker's safety training is warranted. Our hypothesis is that the sheer complexity of a construction project and its safety-related information and knowledge make difficult their full communication to workers. Consequently, the major challenge that needs to be met is what, when and how safety training could be administered using BIM-based construction project together with an emerging communication medium such as Virtual Reality (VR).

2. Background

Several studies show that Information and Communication Technology (ICT) is often advocated to contribute to safety and risk management. In the following section, an overall view of the research trends and applications is provided:

1. Knowledge based systems: systems and models that take into account data and experience from previous projects in order to support decision making for risk assessment. (Qi et al. 2011).

2. Automatic rule checking: design assessment based on the use of computer programs to asses a design and objects configuration with regulations via specific algorithms and BIM-compliant platform (Getuli et. al 2017) (Schwabe, Teizer, & König, 2019).
3. 4D BIM: Construction schedule information integrated into a 3D BIM to increase dynamic visualization of safety procedure. (Getuli & Capone, 2018)(Boton, 2018; Choe & Leite, 2017)
4. Clash detection: for a safety design purpose, clash detection is mostly used for construction workspaces planning and management

All the aforementioned models have been classified as Reactive IT-based safety systems that are able to provide simulation virtual prototyping to assist safety risk identification and safety planning.

5. Moreover, due to the fact that construction projects have a habit of changes during the execution phase, a second group of models, classified as Proactive IT-based safety systems have been proposed in literature(Guo, Yu, & Skitmore, 2017). These models, somehow integrated with BIM environments, are able to collect real-time data from the sites for further analysis and give immediate warning or feedback to the site personals.
6. Virtual Reality (VR) and related technologies that are mainly used for construction education and training which consist of an interactive computer environment able to introduce an external user in a real-time simulation of the real works.(Li, Yi, Chi, Wang, & Chan, 2018; Sacks, Perlman, & Barak, 2013)

All the aforementioned technologies have been used for safety training to improve construction site operation safety but from the above-mentioned background it has been emerged that, despite of considerable development work, most of their focus has been developed for testing or developing new technologies to mitigate safety risks. In addition, another knowledge gap is that there are nearly no studies investigating how BIM and VR can be simultaneously integrated in real projects for construction safety training by using a coherent and standardized protocol.

For these reasons, in this research, the authors propose a **safety training protocol** based on BIM-enabled virtual reality activity simulations.

3. Research objectives and method

As mentioned before, the aim of this work is to draw up a prototype protocol for the design and administration of safety training to construction workers based on an innovative and interactive learner-centric approach developed to be extensively suitable for different construction projects and moreover of easy implementation. In order to achieve this, the research focused on the following objectives:

- <u>Construction site simulation using Immersive Virtual Reality</u>: the training protocol is centred on the trainee's direct real-scale experience of an interactive virtual environment representing the real site with the related construction activities;

- Integration with a BIM-based construction site project: all the information required for the design, management and administration of the safety training are acquired and consistently integrated in a BIM-based health and safety plan;
- Ease of implementation: the training methodological and operational framework shall be oriented to its users, namely OHS trainers and trainees, avoiding possible implementation barriers: (a) no need for ICT specialized knowledge for the practitioners; (b) adoption of ergonomic and user-friendly immersive VR technology; (c) low costs for the implementation and (d) high portability of the hardware setup.

The methodology adopted in this research is discussed in the following paragraphs.

1) VR safety training

When dealing with a well-established matter as it is safety training by using new tools as it is Virtual Realty, the risk of focusing just on the technological aspects of the implementation could threat the robustness of the approach. To prevent this, prior authors' concern was to address comprehensively the training process, identifying three methodological issues: planning, management and administration of such a training. On the basis of the aforementioned aspects, this research work is driven by the following key questions:

- Planning: Which are the VR training typologies and the related training aims? When do the VR training sessions have to be administered? Which types of VR training have to be related to each session? Who are the appointed trainees for each VR training session?
- Management: How do the training contents are developed for the planned VR training session?
- Administration: Where the VR training sessions take place? How many trainees are involved in each VR training session and for how long? Which modes of VR training experience sharing and trainees' involvement are provided? Who are the OHS practitioners involved and which are their roles during the VR training session?

The integrated solution to these questions is reported in the wider context of the whole VR training development and administration workflow discussed in the paragraph 4.

2) Operational framework

Besides the methodological issues outlined above, the technical implementation and administration of the proposed VR training protocol is centered on the following three requirements:

- BIM-compliancy: The assumption is that a BIM construction plan is the initial data source -site's 3D geometries and information- for the generation of the scenarios of the VR safety training sessions.

- Game technology: The authors adopted a game technology solution based on the game engine "Unity". This platform allows the customization of the user experience during the immersive VR training session and his interaction in the virtual site scenario.
- Mobile VR: In order to mitigate the implementation costs and enhance the hardware setup portability in a construction site, thus facilitating the implementation of the proposed protocol, immersive VR for mobile devices based on the Google Cardboard platform was selected as target technology for the development and administration of the VR training experiences.

3) Use of a case study

The VR training protocol was applied to a construction project based in Italy that served as case study for the development of the training sessions' contents and their implementation. The case study consists of a construction of a new complex of three one-storey buildings with cross-laminated timber (CLT) structure atop an existing office facility in the city of Pisa, in central Italy.

4. Virtual Reality Training Protocol

This research aims to define an operative protocol for the planning, management and administration of safety training for construction workers centred on a BIM-based construction plan and administered by mean of immersive VR simulations of the site's layouts and construction activities. In this paragraph, the training protocol and the related dataflow is presented in Figure 1 and discussed in terms of its methodological aspects and tools. With reference to Figure 1, the five identified steps are numbered and individually discussed in the following paragraph.

4.1 Step 1 - Federated BIM Model acquisition

The VR training sessions are set in a BIM-based virtual reproduction of the construction site that must be consistent in term of layout, facilities and equipment in the same configuration the worker will find in site after the training. For this reason, it is necessary to acquire the BIM model of the construction comprehensive of the all building elements eventually arranged in multiple mono-disciplinary models provided from different firms – e.g. architectural, structural and MEP. Then, once assessed the model's integrity, the process can move to the BIM implementation of the site plan, construction schedule and safety procedures.

4.2 Step 2 - BIM construction schedule and site plan implementation

In this phase the acquired federated BIM model is integrated with a construction schedule and site layouts' plans. Furthermore, for the building elements considered relevant for the training purposes according to the H&S manager's experience, the required workspaces and H&S data related to their construction activities are introduced in the BIM Model for the later training planning phase.

Aside the adopted BIM authoring platform, this is achieved through three methodological steps comprising: (1) the construction schedule implementation, (2) the site modelling and, finally, (3) the 4D construction simulation. In particular, according to the proposed protocol's aims, the BIM site layout modelling is oriented to the definition of an effective data source for the implementation of the site scenarios where the immersive VR training sessions will be set. For this reason, with reference to previous authors' works, two modelling scales are here distinguished: *layout scale* and *activity scale*.

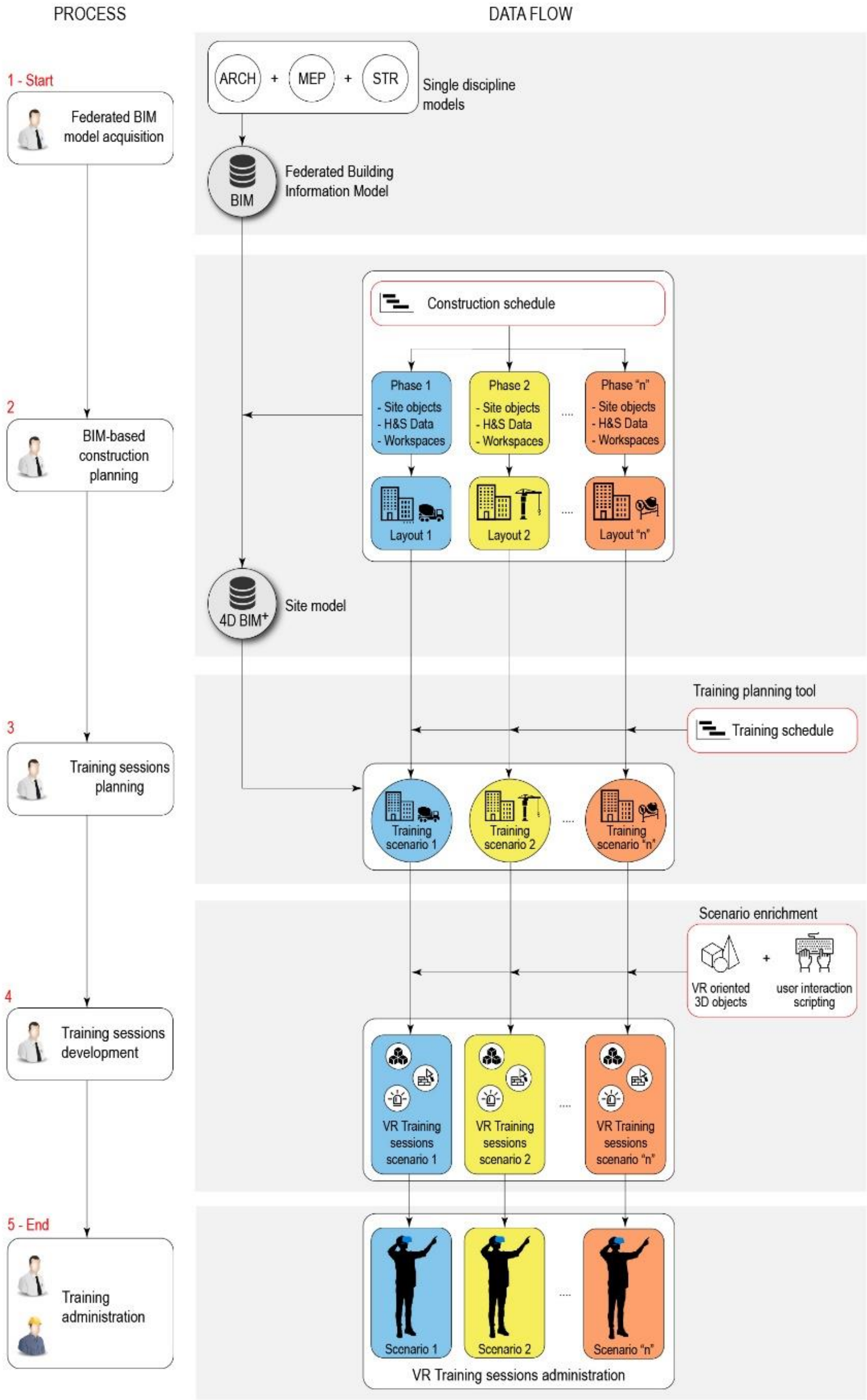


Figure 1: Virtual Reality training protocol application process and data flow

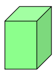
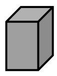
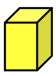
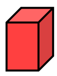
Activity modelling

The modelling of a construction activity in a BIM environment represent an open issue despite being addressed with different solutions based on the representation of the site space usage - usually called workspaces- via parametric objects with attached non-geometrical information (e.g. time needed for completion, risks, etc).

For this study, aiming to the immersive VR visualization of the construction activities for safety training purposes, an approach developed from the activity workspaces modelling of (Getuli et al. 2018) with the integration of specific H&S data, is proposed as follow which consist of four data packages:

- Activity workspaces: The working-cloud that spatially represents the construction execution of a building component is modelled via 3Dimenstional objects consisting in parametric bounding boxes conveniently arranged around the component itself. These static volumes, virtually limiting the spaces that are dynamically occupied in site during the construction activity for different needs and times, are classified via the proposed colour scheme (Table 1) in order to communicate both in the BIM environment, to the H&S manager, and in the immersive VR simulation, to the trainee, their future usage.

Table 1: Workspaces definition

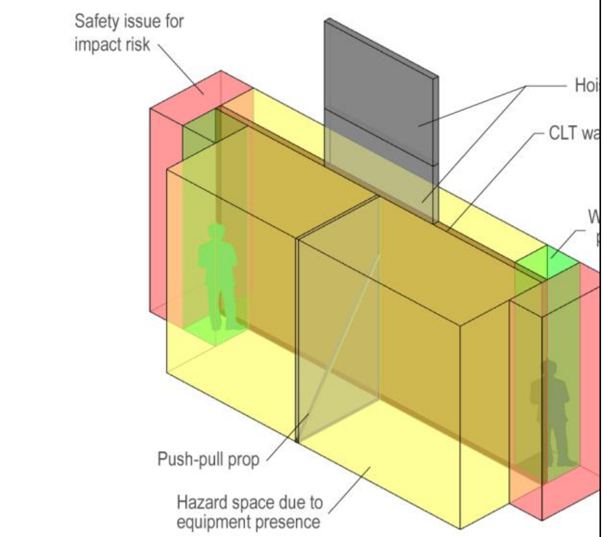
	*Labor crew space*: represents the space required by the labor crew installing the construction product		*Equipment space:* represents the space required by the equipment supporting either the construction product or the labor crews
	*Hazard space:* represents a hazard space generated by a Labor crew space or Equipment space		*Safety space:* represents a tolerance (safety distance) between two workspaces to prevent safety hazards such as collision between two spaces or a tolerance space from objects falling from height

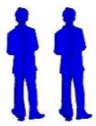
- Labor crew members: They are represented via parametric objects that, besides carrying all the relevant information for the identification of the worker involved in the activity (e.g. name and surname, company, qualifications, etc), are inserted in dependence of a “labor crew space” and serves for the understanding of their position and role during the modelled construction activity for the later development of the VR training contents.
- Work sequence and safety procedures: The construction activity is decomposed in phases/tasks for which the operational procedures and the related safety directions are defined (see Table 4). This information is then integrated as additional text data into the BIM object of the construction activity and serve for the later implementation in the VR training contents development.

- Construction and risk data: Information related the required equipment, their costs and the prescribed Personal Protective Equipment (PPE) are integrated in the construction activity model along with the risk evaluation outcomes for a pre-defined set of risks.

With reference to one of the construction activities object of the VR training experiences developed in the case study (i.e., CLT wall panel installation), the example of the parametric BIM object which is based on the method proposed above is reported in Table 2.

Table 2: BIM model of a CLT wall panel installation activity with safety training informative contents (geometries and data)

<table>
<tr><td colspan="2">
Lowering and alignment of the CLT wall panel</td><td colspan="2">

Activity workspaces - BIM model</td></tr>
<tr><td colspan="4">Labor crew</td></tr>
<tr><td></td><td colspan="3">Crane operator: Worker assigned to the crane operation in order to lift the CLT wall panels from the truck and to move and to lower them to their designed location. He must operate from a convenient position to visually check the load during its moving and to communicate by voice with the other labor crew members.</td></tr>
<tr><td></td><td colspan="3">Workers: Carpenters assigned to the alignment and fastening of the CLT wall panels. They must manually drive the panels to their final position and then brace and fasten them once they are correctly aligned. They must communicate with the crane operator during panels' moving.</td></tr>
<tr><td colspan="2">Work sequence</td><td colspan="2">Safety procedures</td></tr>
<tr><td colspan="2">1) Loading/unloading
A worker on the ground ensure the correct fastening of the hoist belts to the CLT panel that has to be lifted. Once the load is attached, the crane operator proceeds lifting the CLT panel and moving it to its final location or to a dedicated temporary storage area.</td><td colspan="2">- Check the consistency with the installation sequence of the CLT wall panels during their positioning phase.
- Check the correct fastening of the hoist belts and the conformity of the lifting accessories before each lift.</td></tr>
<tr><td colspan="2">2) Fastening to concrete footing
The crane operator moves the CLT panel towards its assigned location where it is received from two workers that manually handle it during the last phase of its lowering. Once correctly aligned, the workers fix the required push-pull props to the CLT panel and fasten it to the concrete footing.</td><td colspan="2">- Pay attention during the moving of the CLT wall panels in order to prevent their collision with building parts, pieces of equipment and workers.
- Keep the CLT wall panels attached to the crane until the completion of its fastening to the concrete footing and its bracing with push-pull props, in order to prevent roll-over.</td></tr>
</table>

3) *Fastening to the adjacent panel* Once the workers have braced the CLT wall panel and fastened it to the concrete footing, they fasten it to the adjacent wall panels making use of a rolling scaffold to work at level higher than 2,00 m above the floor. Finally, the workers release the hoist belts from the panel and make signal to the crane operator to load the next panel.	- Make use of a rolling scaffold positioned on the inner side of the CLT wall panels to carry out their lateral fastening to the adjacent wall panels and the following releasing of the hoist belts.

Construction data		Risk data (0-5 scale)	
Equipment 1:	Push-pull prop	*Fall from high:*	2
Equipment 2:	Rolling scaffold	*Crush:*	3
Equipment 3:		*Hit or struck by:*	1
PPE 1:	Safety helmet	*Loads manual handling:*	0
PPE 2:	Safety shoes	*Noise:*	0
PPE 3:	Protective gloves	*Cut/pierce:*	2

4.3 Training sessions' programming

In this stage the H&S manager programs the training sessions on the basis of the construction schedule and of the contents of the 4D BIM model consisting, for each construction phase, in all the geometries and data related to the site layout, objects, facilities and the building elements with the associated construction activities. Therefore, the required information is available to address the following key-questions related to the programming activity of the safety training:

- What? - Definition of training typologies, aims and contents
- Why? When? – Definition of the criterion for the decision of training schedule (date-typology-trainees)

Once defined the training schedule, for each planned training scenario (site layout + activities) the 4D BIM site model is filtered so that the needed contents are available to be transferred in the game-engine environment for the development of the immersive VR training experiences.

4.4 Training typologies

The authors investigated which safety training sectors and contents' transfer methods were better enhanced by the adoption of immersive virtual reality technologies to provide the trainee's first-person real-scale experience of the site and the related construction activities in a safe virtual environment (V; Getuli, Giusti, Capone, Sorbi, & Bruttini, 2018)

As a result, for the proposed protocol, three training typologies are defined in terms of comprehensive aims and contents (Table 3). Furthermore, the decision criterion is provided for each training typology based on two construction schedule milestones, namely "**Layout switch**" and "**New component first assembly**". Detailed specification for the training decision method is given in the following paragraph.

Table 3: VR safety training typologies and characteristics

Layout-oriented training	**Aims**	- Activities coordination and workspaces management - Understanding of workers', materials' and vehicles' site circulation - Illustration of site's facilities and zones access and usage authorization
	When [training milestone]	Before each site layout transformation [called "**layout switch**" in Figure 4 -training schedule-]
	Contents	- *Site areas; Equipment, facilities, plants; Activity workspaces; Paths; Specific risk zone*
Building component first assembly training	**Aims**	- Illustration of site-specific and activity-related risks trainees are exposed to and safety measure to adopt consequently - Visualization of construction activity workspaces configuration
	When Training [milestone]	Before every first assembly of a new component [called "**new component first assembl**y" in Figure 4 -training schedule-]
	Contents	- *Workers; Equipment, facilities, plants; Activity workspaces; Paths; Safety procedures; Specific risk zones*

Emergency management training	**Aims**	- <u>Type 1</u>: Worker's illness or accident
		  - Illustration of illness or accident related safety procedures
		- <u>Type 2</u>: Fire management
		  - Illustration of emergency procedures, equipment position and emergency circulation
		  - Understanding emergency circulation in terms of escape routes, assembly areas and rescue vehicles' access and paths

	When [training milestone]	Before each site layout transformation [called "**layout switch**" in Figure 4 -training schedule-]
	Contents	- *Emergency subject; Workers; Emergency equipment and rescue vehicles; Paths and escape routes; Safety procedures; Specific risk zones*

4.5 Training schedule for VR safety training programming

For the training sessions programming activity, based on the typologies described in the previous paragraph, the H&S manager is required to determine a training schedule -specifying dates, training contents and trainees involved- in accordance with the construction schedule. In fact, the training schedule serves the dual purpose of programming the training contents development and of ensuring a correct timing in the relationship training-mission. In support of the H&S manager's decision, a training schedule criterion is proposed, based on the individuation of the two training milestones upon the construction schedule:

- *Layout switch*: Before each site layout relevant transformation (e.g. changes in the circulation, area function transformation, plant or facilities assembly/dismantle, etc.) the workers that will operate in a changed working environment have to be involved in VR training sessions that regard their safety behaviours at a layout-scale.
- *New component first assembly*: Before that a relevant building component is introduced in site or assembled for the first time from an assigned labour crew, the workers involved have to be trained for the procedures and risks related to the activity in the specific site configuration and in respect of the near ongoing activities. Relevant changes in the assembly procedures of a building component that has already been built or the occurrences of relevant specific activity-related risks that were not present before, count as first assembly for the determination of the training milestone.

The application of the decision method, in accordance of the training milestones specified above for each training typology, is shown in Figure 4. Once determined the training milestones, the H&S manager, along with the construction manager and the companies' site managers, decide convenient dates for the training sessions to be administered (e.g. one week – three days in advance respect the milestone's date).

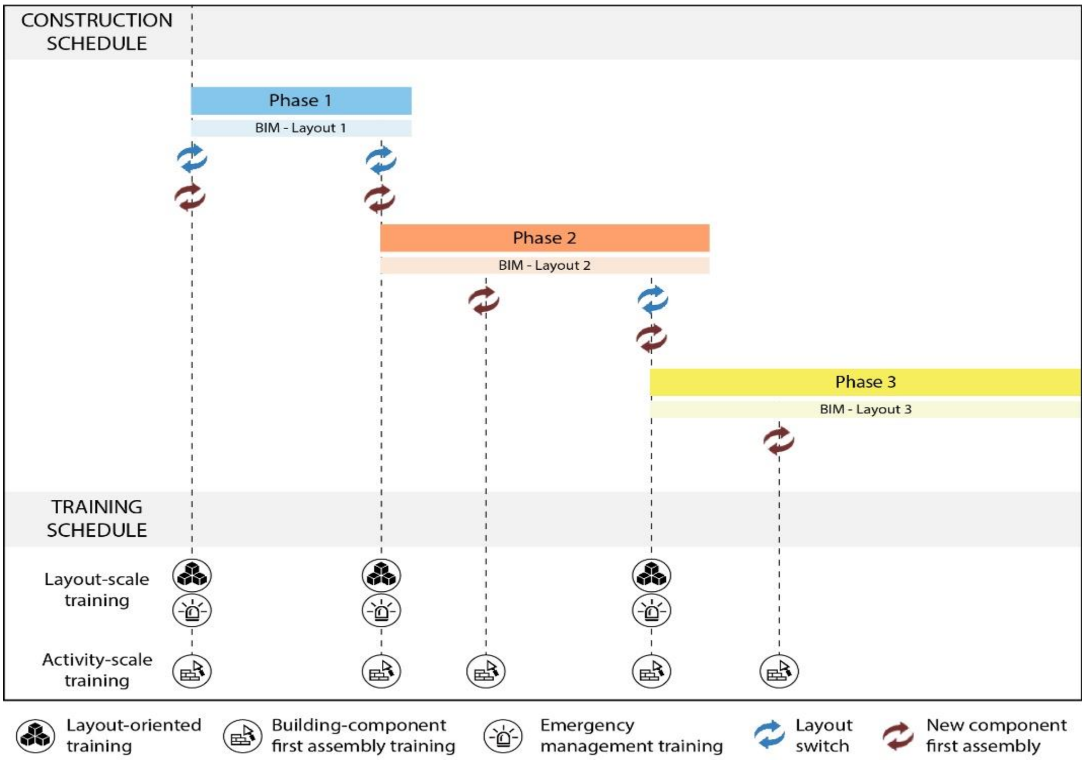


Figure 2: Proposed safety training schedule

4.6 Training sessions' development

For the development of training scenarios, the BIM-based 3Dmensional models and data referred to a certain training scenario are extracted and imported in a game-engine platform where every single training experience is developed giving attention to the trainee's relation with the virtual site reproduction in terms of: (a) What the trainee sees; (b) How the trainee interacts with what he sees.

Both the aforementioned aspects are affected from the choice of the knowledge transfer method and of the target VR technology for the delivery and administration of the training experiences. In this regard is recalled that for the proposed protocol is considered a mobile VR technology.

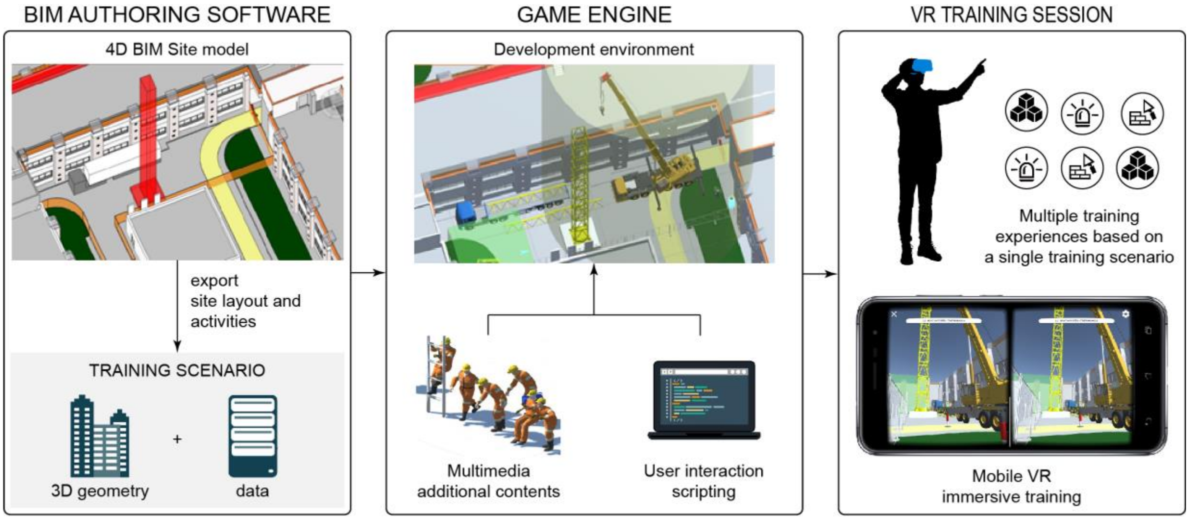


Figure 3: VR training contents development workflow

4.7 VR-oriented graphical enhancement and additional contents implementation

In the proposed protocol two different developing environments - BIM and game engine - are determined and kept separated in respect of their purposes. In fact, on one hand the processes of construction scheduling, site planning and safety training data integration are carried out on a BIM authoring platform and results in the 4D Site Information Model discussed before, while, on the other hand, these same contents are further edited and enriched in a game engine platform to deliver a suitable environment for immersive VR experiences. In order to achieve the training objectives, the trainee must proceed in a learning path through the virtual reproduction of the site where he can not only move around but also interact with a vivid and realistic environment. For this reason, since the Level of Development (LOD) of the site's objects contained in the Site Information Model is sufficient just for the scheduling and planning purposes but not fulfils the realism requirement of an immersive VR experience, their replacement with more graphically detailed objects is to be considered. Furthermore, auxiliary virtual objects that support the trainee to explore the virtual environment and to access and receive safety training-related information have to be added in the game engine environment.

5. Conclusions

This work contributes to provide a standardized protocol for a viable integration of BIM and VR technologies for construction safety training in real projects. A 5-steps process have been drawn and procedures defined to support the VR training planning, management and administration. In particular, the technological aspects have been addressed with the adoption of game technology, to provide a coherent data flow from the BIM environment to the VR training experience delivery, while, from a methodological perspective, standard training typologies, with related contents and aims, have been paired with a decision support tool based on the construction schedule, to fully determine the training sessions.

At this stage, the proposed protocol has been developed and implemented in terms of planning and scheduling of three VR training sessions regarding the case study (installation of wall, beam and roof panel of the CLT structure). Those experiences are currently being administered to the workers involved in the construction execution. The results will be published in future publications.

Acknowledgements

The authors acknowledge the INAIL -National Institute for Insurance against Accidents at Work- (Italy) for funding this research and CNR -National Research Council- for providing the case studies.

References

Behm, M., 2005. Linking construction fatalities to the design for construction safety concept. Safety Science 43 (8), 589–611.

Niza, C., Silva, S., Lima, M.L., 2008. Occupational accident experience association with workers' accident explanation and definition. Safety Science 46 (4), 959–971.

Sokas, R.K., Jorgensen, E., Nickels, L., Gao, W., Gittleman, J.L., 2009. An intervention effectiveness study of hazard awareness training in the construction building trades. Public Health Reports 124 (1), 161–168.

Activity Report CPT 2017 "Annual report for construction safety monitoring" (available online http://www.cncpt.it/Contents/Documents/Rapporto%20CNCPT%202017_%20DEF-REV.pdf)

Abdelhamid, T., Everett, J., 2000. Identifying root causes of construction accidents. Journal of Construction Engineering and Management 126 (1), 52–60.

Tam, V.W.Y., Fung, I.W.H., 2011. Tower crane safety in the construction industry: A Hong Kong study. Safety Science 49 (2), 208–215.

Eastman, C., Teicholz, P., Sacks, R., Liston, K., 2011. BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors. Wiley.

Qi J, Issa R.R.A, Hinze J, Olbina S (2011) "2011 ASCE International Workshop on Computing in Civil Engineering, June 19, 2011 – June 22, 2011" Integration of safety in design through the use of building information modelling: 698–705

Getuli V., Mastrolembo Ventura S., Capone P. and Ciribini A.L.C (2017) "Procedia Engineering" BIM-based code checking for construction health and safety 196: 454-461

Boton, C. (2018). Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation. *Automation in Construction*, *96*(September), 1–15. https://doi.org/10.1016/j.autcon.2018.08.020

Choe, S., & Leite, F. (2017). Construction safety planning: Site-specific temporal and spatial information integration. *Automation in Construction*, *84*(October), 335–344.

https://doi.org/10.1016/j.autcon.2017.09.007
Getuli, V;, Giusti, T., Capone, P., Sorbi, T., & Bruttini, A. (2018). A Project Framework to Introduce Virtual Reality in Construction Health and Safety. *AlmaDL Journals*, *New Frontiers of Construction Management Workshop*, *09*(13), 166–175. Retrieved from https://in_bo.unibo.it/article/view/8830/8950
Getuli, Vito, Mastrolembo, S., Capone, P., & Ciribini, A. L. C. (2016). A BIM-based construction supply chain framework for monitoring progress and coordination of site activities. *Procedia Engineering*, *164*(June), 542–549. https://doi.org/10.1016/j.proeng.2016.11.656
Getuli, Vto, & Capone, P. (2018). Computational workspaces management : a workflow to integrate workspaces dynamic planning with 4D BIM, (Isarc).
Guo, H., Yu, Y., & Skitmore, M. (2017). Visualization technology-based construction safety management: A review. *Automation in Construction*, *73*, 135–144. https://doi.org/10.1016/j.autcon.2016.10.004
Li, X., Yi, W., Chi, H. L., Wang, X., & Chan, A. P. C. (2018). A critical review of virtual and augmented reality (VR/AR) applications in construction safety. *Automation in Construction*, *86*(October 2017), 150–162. https://doi.org/10.1016/j.autcon.2017.11.003
Sacks, R., Perlman, A., & Barak, R. (2013). Construction safety training using immersive virtual reality. *Construction Management and Economics*, *31*(9), 1005–1017. https://doi.org/10.1080/01446193.2013.828844
Schwabe, K., Teizer, J., & König, M. (2019). Applying rule-based model-checking to construction site layout planning tasks. *Automation in Construction*, *97*(November 2017), 205–219. https://doi.org/10.1016/j.autcon.2018.10.012

A digitized environment for H&S and fire safety management in the heritage building "Palazzo Vecchio"

Tommaso Giusti[1, *], Pietro Capone[1] and Vito Getuli[1]
[1]Dipartimento di Ingegneria Civile e Ambientale – Università degli Studi di Firenze
* email: tommaso.giusti@unifi.it

Abstract

Target

This contribution is part of a wider research dealing with management of complex activities in Palazzo Vecchio in Florence. The goal of the research is to individuate the best combination of building intervention and management strategies to reach both safety and comfort for occupants.

The goal of this contribution is to describe the research first results with respect to H&S and fire safety engineering studies.

Context

Palazzo Vecchio is the town hall of Firenze and it is an ancient building, since its origins built to be the representative location of the political power of the town. Palazzo Vecchio hosts a lot of very important activities for the city and the goal of the public administration is to assure health and safety both to the workers and to the public visiting the building.

Description

Fire and Health and Safety requirements can be managed in such a complex framework only making use of innovative approaches preferably by using digitized design processes, in order to reach design objectives managing building constraints and design requirements within a Common Data Environment (CDE). Such study allow us to suggest some intervention on the building useful to reach the main objective (people safety).

A large part of the research is related with building modelling to understand fire spread and exodus performances of the building, defining as consequence the management strategies to assure the fixed performances; this together with Health and Safety management for workers inside the building.

The second part of the research is related with the creation of the CDE, that stores the validated and collected information and provides exactly the information to the decision maker.

Future results and developments

Important results are related to FSE design and to the definition of safety masterplan of the building. Future developments are related with the CDE construction.

Keywords: Models for design and construction, Building Information Management, Innovative technologies for new process management.

1. Introduction

This contribution intend to explain the first important results of the research project dealing with management of complex activities in Palazzo Vecchio. The research project puts together Dipartimento di Ingegneria Civile e Ambientale of the Università degli Studi di Firenze and Comune di Firenze, in order to reduce health and safety risks in the historical heritage building of Palazzo Vecchio, with the specific interest in fire risk management.

The compatibility between building and activities requirements is a complex problem, both in terms of occupant comfort and in terms of compliant to regulations. National construction regulations often consider peculiar exceptions in the case of historical buildings application, compensating expected building performance with management procedures, in order to obtain an equivalent level of compliant. The manager of historical buildings inside which today activities are performed, has to guarantee safety and comfort of occupants, together with the preservation of the building and artistic contents (Giusti, 2014). A simple application of existing regulations cannot be adopted because of a lacking harmonization among them (Nassi et al, 2008, Marsella et al. 2010); such a complex framework can only be managed making use of innovative approaches, preferably by using digitized design processes in order to reach design objectives managing building constraints and design requirements within a Common Data Environment (CDE). This way both safety and comfort goals are reached, combining respectful interventions on building with activity management strategies.

Such an approach has been used to manage Fire Prevention together with Health and Safety in the Florentine building “Palazzo Vecchio”. The whole research is split into three steps: the first and the second are concluded and produced a methodological approach that leaded to the fire safety masterplan of the building together with health and safety for workers; the third step is related to the CDE development to provide a information system containing data relating to the building and activities in order to create a database, a reference point for retrieving information and making subsequent analyses.

1.1 Palazzo Vecchio

Palazzo Vecchio is the town hall of Firenze, since its origins built to be the representative location of the political power of the town. In Palazzo Vecchio three different blocks can be identified, corresponding to the historical extensions of the building. The original nucleus is the medieval one, characterised by the tall tower facing “Piazza della Signoria”; the second block is the renaissance extension that comprehends the “Salone dei Cinquecento”, the main hall of the palace; the latest part is the one rises around the third courtyard.

The building has one underground level, four levels out of ground and two mezzanine floors; the architectonical layout of rooms and stairs is quite complex because of the historical development of the palace. Almost all the rooms in use today were created in the past with different purposes with respect to the today use; only the two main halls (Salone dei Cinquecento and Salone dei Duecento) were originally create to host public assemblies and this is the today destination of use. The medieval and the renaissance parts are open to the public because they are a museum; the most recent part contains offices of the local administration.

As said, Palazzo Vecchio hosts a lot of very important activities for the city and one of the main goal of the public administration is to assure health and safety both to the workers and to the public visiting the building.

2. Research proposal

The research proposal, well described in (Giusti, 2017), has the goal to create a system of management strategies and building interventions to assure the goal of safety for occupants in Palazzo Vecchio. The aim of the study is to harmonize safety of occupants and workers, preserving the building characteristics, with an all-inclusive approach able to complete the gap to reach the building and occupants safety.

The research is developed in three main branches (Figure 1):

1. Fire Safety Engineering (FSE): it is necessary to make the building able to have the required performance with respect to people and contents protection.
2. Buiding Design for Safety (BDS): health and safety for workers can be guaranteed applying the BDS method to working places, as referred in literature (Ciatti et al, 2017).
3. Common Data Environment (CDE): the creation of a BIM-based collaborative process by using a Common Data Environment is the chosen way to ensure the harmonisation of the adopted design and maintenance strategies to assure H&S Management in Palazzo Vecchio, keeping them efficient for a long time.

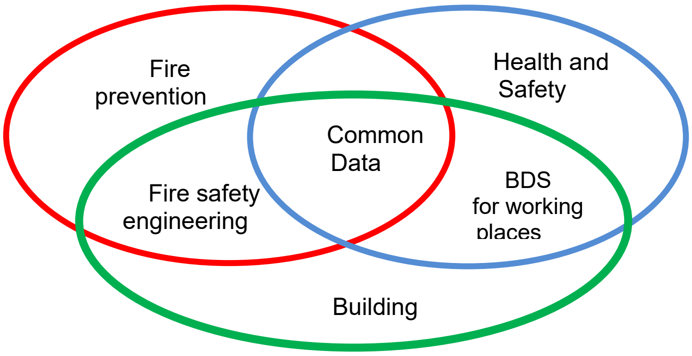


Figure 1: Research framework (modified from Giusti, 2017)

This contribution describes points 1 and 2 of the list, performed with instruments able to create data to be used for the CDE, that is currently under construction.

3. FSE for the fire safety masterplan

This part of the research is based on a methodological working flow that was produced (Giusti, Getuli, Capone, 2018) and it was applied to the building we study. The proposed approach represents a general technical reference for the organic integration between the prescriptive approach and the performance one in fire prevention in historic buildings. Workflow consists of eight steps and follows a logical process that involves the use of cyclical analysis for the in-depth analysis necessary to resolve the identified critical issues.

The main outcomes of the approach are related to:

1. Strategical mitigation actions;
2. Fire prevention masterplan definition;
3. FSE simulations.

Strategical mitigation actions

As a result of the identification of the main fire risk factors on a building scale, strategic decisions have been implemented to mitigate the factors that can deeply influence the whole project. The reiteration of the mapping-analysis-mitigation actions of the risk factors at scale of the building, leads to optimizing the interventions aimed at eliminating the maximum possible number of macroscopic criticalities.

Fire prevention masterplan definition

Once defined the strategical mitigation actions, was possible to outline the fire prevention masterplan of the whole building, that is based upon four main items (1. Division of the areas to the museum destination from those to the offices, 2. creation of fire prevention filter in the middle of the building, corresponding with the main hall Salone dei Cinquecento, 3. Creation of a "circulation" of the escape routes, in order to guarantee more exit routes in case of fire, 4. Definition of a new emergency plan for the whole building evacuation and management actions to maintain unchanged in time the stated level of risk).

Masterplan definition is one of the most remarkable result of this part of the research (Figure 2). Building's needs of conservation were safeguarded exploiting the hidden potential of the palace. It was possible to create an effective network of paths and compartments just giving back dignity to some of the building's rooms today reviled.

Figure 2: example of the fire prevention masterplan at the third floor of the building.

Fire Safety Engineering simulations

Fire Safety engineering simulations were undertaken to resolve the critical issues that cannot be tackled with prescriptive interventions. This is because the particular artistic-architectural constraints have limited, under various aspects, the respect of the current regulations. The performance approach has been configured as the only one able to find an effective solution to the problems encountered and, at the same time, to be non-invasive while respecting the context in which it is inserted.

For each area of the building affected by an analysis with a performance approach, in-depth analyses are carried out relating to:

- identification of the safeguard objectives (safeguarding human life, protection of the works or of the building);
- identification of fire scenarios and computational modelling of fire spread, also in order to monitor the presence of pollutants compatible or not with decorated surfaces and works of art;
- determination of the reference parameters for safeguarding life (and works, if required by the specific context);
- analytical determination and by means of computational modelling of exodus times from the areas identified.

Specifically, studies and performance modelling were carried out regarding the spread of the fire, and therefore of temperatures, smokes and pollutants, on:

- main staircases (Vasariano staircase, Stairway connecting the Elements Quarter and the Salone dei Cinquecento);
- Arnolfo tower;
- Salone dei Cinquecento.

Fire simulations are performed using FDS software, having output related to temperature, visibility and pollutant; from the models of staircases and tower we demonstrated that the building is not able to guarantee a sufficient time for building’s occupant exodus; the only way to mitigate fire risk in those spaces is to apply procedures that are able to avoid the fire starting.

From the model of Salone dei Cinquecento, we demonstrated how is possible to make the hall working as a “fire filter” for the whole building, just by means of the installation of automatic opening mechanism on the windows. From the fire spread simulations we determined the Available Safe Escape Time (ASET=800s).

Furthermore, performance modelling was carried out regarding the determination of the exodus times on:

- Museum of Palazzo Vecchio, with all the connected environments and Salone dei Cinquecento;
- Nineteenth-century portion used as offices.

Required Safe Escape Time (RSET), referred to the ISO/TR 16738, was calculated using an exodus modelling software (Pathfinder software in SFPE mode).

Two main models were done, one for the whole museum part and another for the offices part. From each model we found the total escape time RSET.

In Table 1, results in terms of ASET and RSET are resumed for the considered main scenarios, together with some notes useful to explain important practical relapses involving building and management.

4. BDS for H&S of workers

A deep analysis about Health and Safety for workers in Palazzo Vecchio was performed applying Building Design for Safety (BDS) approach (Figure 3). BDS tents to link all the collected data (1) concerning H&S, both material (equipment, furniture, …) and intangible (working activity, risk evaluation indexes, …) to the workstation occupied by the man – Figure x. A further step (2) is the risk assessment for each workstation, taking into account also all the relationships between building and workplace. Every workstation can be, this way, analysed in terms of dimensional and performance requirements; then, combining ergonomic issues with H&S risk mitigation, an optimised typological working place is defined (3), able to reduce risk to the root. Combining all the optimised workplace in the rooms we deal with, lead to the creation of a work environment (4) that is Health and Safety upgraded. Passing from step 3 to step 4, compatibility between working activities and building, with respect to fire risk management become essential.

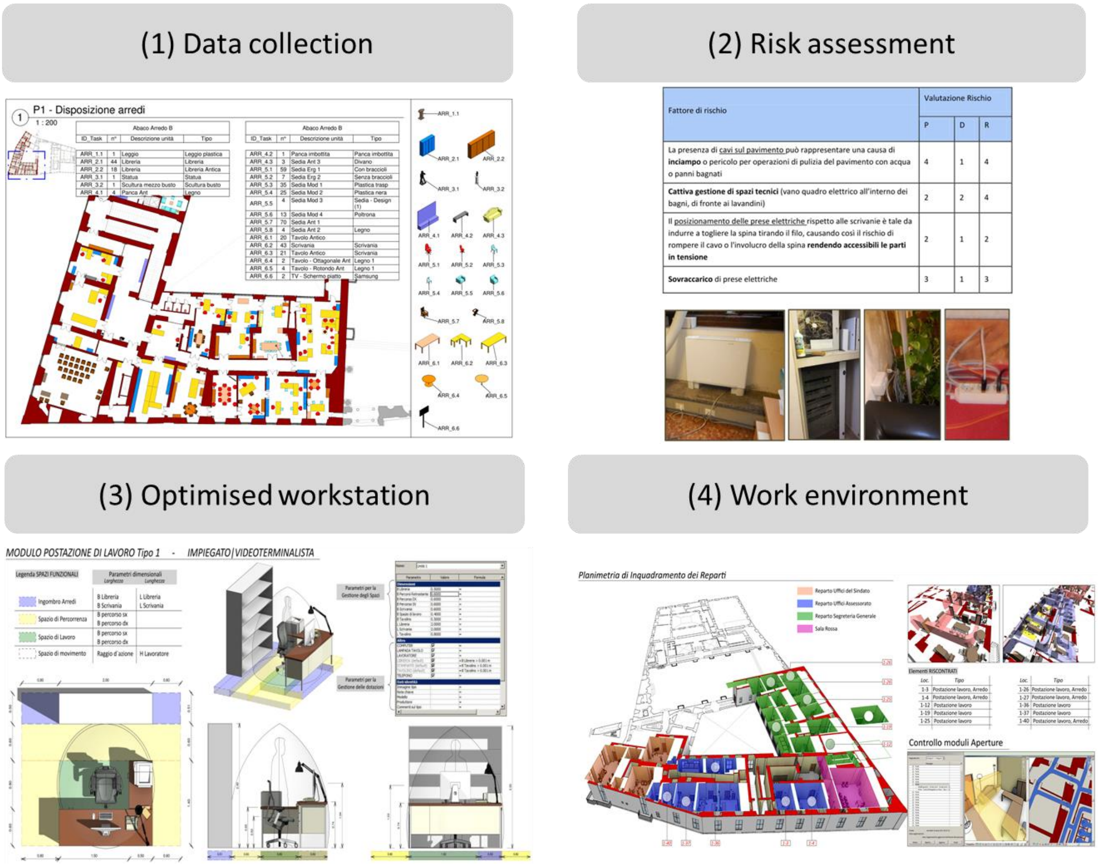
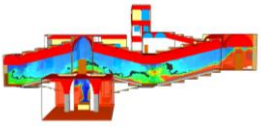
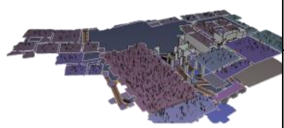
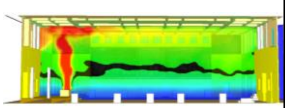
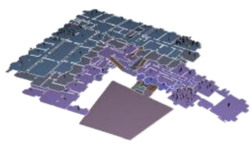


Figure 3: application of BDS approach to Palazzo Vecchio.

Table 1: Synthesis of the FSE modelling and results

CFD fire spread models		ASET	Exodus model		RSET	Description
Main staircase		240 s	Main staircase		930 s	Not acceptable scenario. Scenario that has to be avoid acting with management strategies. No motor vehicle can be stationed near the base of the staircase, each vehicle must be accompanied by personnel trained in fire-fighting and equipped with fire extinguisher.
Arnolfo tower		300 s			654 s	Not acceptable scenario. Scenario that has to be avoid moving combustible materials from the offices at the base of the tower.
Salone dei Cinquecento		800 s			600 s	Acceptable scenario, with installing automatic opening mechanism on the windows and new fire prevention masterplan execution
-		-	Offices staircase		540 s	Acceptable scenario with respect to fire fighter's intervention time. In favour of safety, this scenario neglects the presence of the internal stairs that have been re-opened.

5. BIM-based collaborative process by using a CDE

It is essential to deal with all the aforementioned structural issues (Health and Safety Management and Fire Safety Management in complex buildings) by using a collaborative and integrated workflow in order to avoid approaching matters with traditional paper-based design flows which result labor-intensive, error-prone and highly inefficient. Due to the large quantity of data to be collected and project participants at different levels, the requirements for the technical support of this collaboration in terms of consistency and coherence are very high. For this reasons, a collaborative BIM-based planning for a resilient and technically supported definition of management, data and communication processes has been defined as an essential requirement by the authors. For this purpose, a federated model approach which provides a central coordination model, the so-called Common Data Environment (CDE) has been proposed (Figure 4).

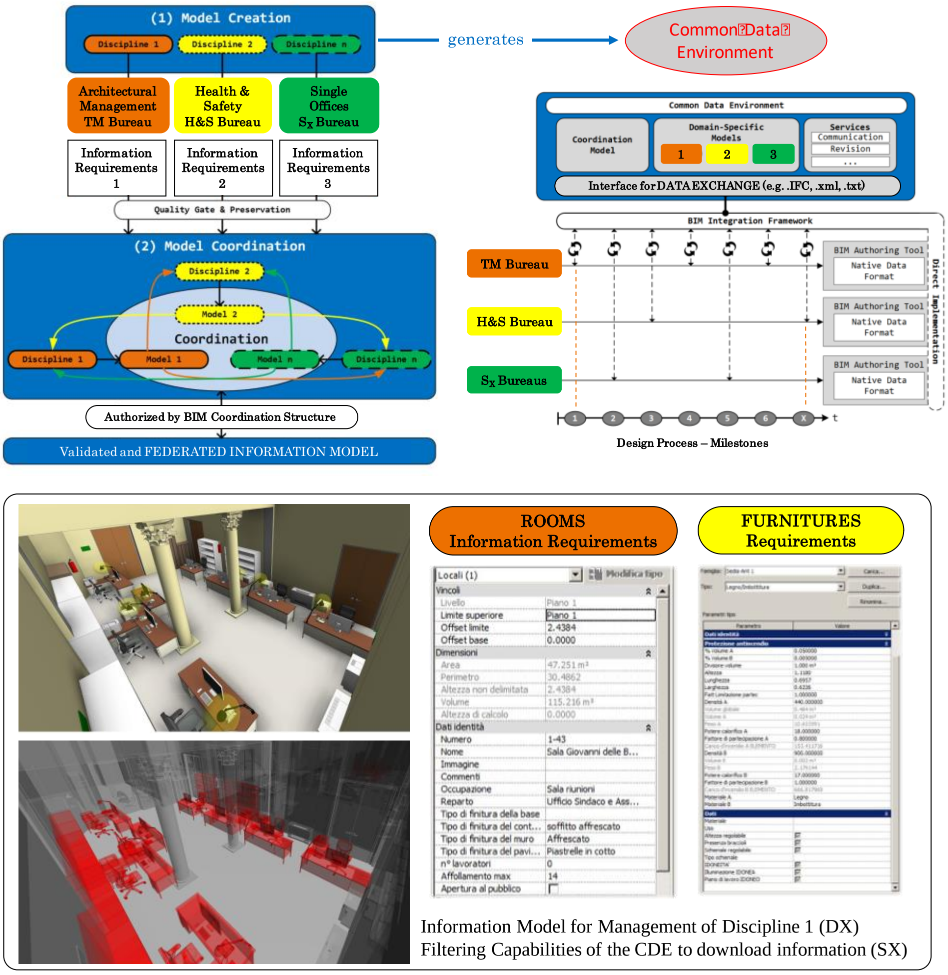


Figure 4: Architecture of the Common Data Environment (from istea 2017).

This model stores the validated and collected information and in turn provides exactly the information, which is required for the collaboration of the three disciplines: (1) Management of the Architectural features of the entire building, (2) Safety and Fire Management, (3) Occupancy Requirements to be guarantee for each office. The CDE, under development, is a single source of information used to collect, manage and disseminate documentation, the graphical model and non-graphical data for the whole project team that will work in such a project. All project participants retrieve the data from the CDE and in turn store their data here after single design flow are carried out. A layered structure architecture of the CDE has been proposed according to details given in Figure 5. At the first level, the Information Requirement for each discipline has been structured. Due to the fact that the investigations in the different disciplines will need different software applications, a file exchange format has been established. This means that individual models produced by different investigations do not interact, they have clear authorship and remain separate. After the investigation, the output data are uploaded within the CDE in order keep the Federated Model updated.

6. Conclusions

The proposed approach, applied to Palazzo Vecchio, brought a series of remarkable results for the improvement of the safety conditions of the occupants and of the goods, above all with reference to fire risk. The methodological approach leaded to define the Fire prevention masterplan, totally respectful of the building's architecture. Most significant results of this part of the research are linked to the exodus time estimation and fire spread simulation. The application of FSE is, this way, related to the determination of the fire-fighting strategies to compensate the risk of safeguarding occupants life. Further, a remarkable improvement of H&S conditions for workers was reached adopting BDS approach for Palazzo Vecchio. Important data and management strategies useful for fire risk control, originated from such an accurate analysis. A huge data gathering of CDE definition has been performed for the whole building, with respect to H&S and fire safety.

In order to make the decision maker able to maintain in time fixed levels of fire risk and H&S risk for workers, in this complex framework is necessary to adopt an innovative source of information used to collect, manage and disseminate documentation; for this reason CDE is currently underway.

References

Ciatti, M., Capone, P., & Opificio delle pietre dure. (2017). *Restaurare in sicurezza: Nuovi progetti per i laboratori dell'O.P.D.* Firenze: Edifir : Opificio delle pietre dure.

Giusti, T. (2014). *Fire risk management for valuable contents in historical buildings.* Place of publication not identified: SCHOLARS' Press.

Giusti, T., Capone, P., Getuli, V. (2017), Management of complex activities in historical heritage buildings: a digitized environment for H&S and fire safety in Palazzo Vecchio, *Re-shaping the construction industry*, *Atti del convegno ISTEA 2017*. Firenze: Maggioli.

Marsella, S., & Nassi, L. (2010). *L'ingegneria della sicurezza antincendio e il processo prestazionale: Guida alla Fire safety engineering ed esempi applicativi*. Roma: EPC libri.

Nassi, L., Carbonara, G., & Marsella, S. (2008). *Sicurezza antincendio per i beni culturali*. Torino: UTET scienze tecniche.

Data, Information and Decision Support System

Design of decision support system for implementation and monitoring of public private partnerships in the Zambian construction sector

Mukalula P M[1*] and Muya, M[2]

[1*] PhD student; Civil and Environmental Engineering; University of Zambia; P O Box 32375, Lusaka, Zambia.

[2] Associate Professor of Construction Management; Civil and Environmental Engineering; University of Zambia; P O Box 32375; Lusaka, Zambia.

* email: musomuko@yahoo.com.

Abstract

Zambia introduced the Public Private Partnership (PPP) law in 2009 in order to narrow the infrastructure gap in the country. The PPP legislation has had difficulties in that it allows cabinet ministers to make decisions on complex issues affecting the implementation of projects. The government ministry responsible has not provided sufficient guidelines regarding evaluation processes in the way schemes may be executed, operated and monitored. In the period 2009 – 2019, very few projects have been accomplished since the introduction of the law. There have also been problems concerning professionals acquiring additional professionals' skills to aid them evaluate and monitor such complex projects. As PPPs are nascent to the country, financial support systems have not been developed to monitor projects funded using weighted average cost of capital (WACC). Upcoming projects would be successful if capital asset pricing models (CAPM) are utilised to inform decision-makers. Findings suggest that technocrats must be trained in risk related aspects for PPP projects to be implemented successfully. Stringent monitoring assisted by a restructuring of the law would need to be instituted. This will encourage investors and conserve financial resources. The research used focus group interviews of professionals involved when the PPP law was implemented. An industry wide questionnaire was distributed to assess the effectiveness of evaluation methods used in decision-making. Spearman's rho was used to appraise the efficiency of the methods used in monitoring projects. A decision support system is suggested for monitoring application and for effective supervision of PPP schemes.

Keywords: Decision support system, Implementation, Monitoring, Public private partnership, Zambia

1. Introduction

In 2009, the Zambian government enacted the PPP law. However, the process of implementing this law has had challenges regarding the assessment of proposals. PPPs signify greater private sector involvement in the delivery of public services. Private sector participation brings with it risk complexities regarding the nature of funding and availability of expertise. Over 90% of PPPs projects on the African continent are externally funded (Zulu and Muleya, 2009). Usually, finance lenders assume about 70 – 75% of the risk on capital costs required for development of large scale infrastructure projects. Evaluation procedures must be effective to raise the confidence of multilateral lending agencies. Additionally, this also deepens the developer's desire to readily own risk during the project. Three factors which have enabled the stage to be set for PPPs in Africa – the changing economic, social and political environment with its globalisation influence, instituted measures for control of public sector borrowing and the vital role that modern infrastructure plays in economic growth and poverty alleviation which has been largely crippled by inadequate levels of public sector income in emerging economies. However, Zambia has had other challenges of inadequate regulatory frameworks and an under developed public and private sectors - which are necessary requisites for PPPs.

2. The quest and demand for PPPs

The quest for governments to involve the private sector in development of infrastructure is one that is encouraged worldwide. Various methods of development are utilised to enable growth of economies. Among such schemes are privatisation, concessions and public private partnerships (Cui et al, 2018). PPPs are viewed as advantageous as they integrate the public and private sectors in a long term partnership. Two factors have enabled governments to partner with private investors. The first reason is that basic infrastructure is fundamentally capital-intensive while the second is the competitive demands on scarce financial resources (Alfen et al, 2009). The aim is to reduce the demand-supply infrastructure gap as well as fulfill social commitments. Public provision of services in developed countries using PPPs includes projects for education, waste water management, public buildings, health services, power and road sector projects (Akintoye, 2009). The telecommunications sector has also been a recipient of huge investments in terms of physical infrastructure.

Demand for public services has led to a new set of circumstances. The OECD (2008) predicted that the world economy is expected to grow at about 3 percent per annum to the year 2030. Much of this growth will be in developing countries. Governments in developing countries therefore have to undertake such service delivery through decentralised management and stock market mechanisms (Heider et al, 2015; Pongsiri, 2002). Governance becomes a matter of concern. Stoker's (1998) definition of governance shows the necessity of accountability, transparency, fairness, efficiency, participation and decency. On the other hand, Alfen et al (2009) expressed governance as a process of evaluation culminating in decision-making. Governance must have transparency in all supervisory processes. In developing the good project governance (GPG) concept, Abednego and Ogunlana (2006) raised the importance of prudent performance in evaluation procedures for PPPs. They saw that project allocated risk was only achievable through good governance which would lead to better project performance. Eight distinguishing factors would comprise the GPG (Abednego and Ogunlana, 2006):

- that right decisions at the right time are the result of contractual parties' active participation;
- contract fairness ensures that the rule of law is the framework that enforced impartiality in application of procedures between the parties;
- information transparency is available to the parties affected by decisions on the project;
- responsiveness being the ability to carry out decisions within a specific timeframe;
- continuous project control and monitoring in achieving common goals amongst stakeholders;
- equality implies that all parties to the contract are equal;
- effectiveness and efficiency ensures that results produced meet contractual parties needs as well as make best use of available resources; and
- accountability in having to fulfill the twofold objective of user satisfaction and community participation

Abednego and Ogunlana (2006) suggested that a contractor's pre-finance (CPF) has the best risk allocation strategy. This strategy shifted the responsibility of financing the project from the owner to the contractors. This also meant that other cash-flow and liquidity problems subsisting with the owner can be overcome (Boamah, 2017; Belkhir et al, 2017). This is because the loan would be made directly between the financial institutions and the contractors. Developers prefer directly dealing with the financiers than going through third parties (Cedrick and Long, 2017).

3. Decision support systems for PPPs

Decision support systems (DSS) assist developers in the management of risks on projects (Kartashova, 2018). There's been much research done on the allocation of risk and monitoring of the same during the implementation of PPP projects between 1998 and 2018. The following conclusions form the accepted understanding (Davies et al, 2018; Akintoye, 2009):

- the assertion that allocated risk structures vary according to contract types placing risk with the contractual party concerned. For instance, Build-Operate-Transfer (BOT) contracts allocate risk to the private sector as opposed to service and management ones;

- economic factors existing in countries such as exchange rates and interest rates are constantly monitored by investors using the PPP method of development;
- that private firms using PPPs are exposed to various risks as they execute projects in other continents than their own; and
- the contractual party able to handle a particular risk should have the capacity to monitor as well as manage it.

For PPPs to succeed, public and private entities have to evaluate risks. These risks can arise from a variety of areas and must be carefully included in contract conditions. Critical risks affecting the scheme are assessed allowing informed decisions to be made during the projects' implementation. These risks are a combination of the political, legal, economic and the social environment prevailing in the country (Joslin and Konchitchki, 2018). The developer will, therefore, have to have a number of hedging instruments. Extended periods of project implementation require financial instruments that have longer maturity to abate interest risk. Financial distress of the project as well as asymmetric information occasions choice of what equity would be used. The safer choice is to have the public share the risk. Reduced exposure of the commercial risk needs decisions aimed at a PPPs project speedy implementation. Liquidity risk must be evaluated to curb a developer's insolvency. Credit risk of this nature can be mitigated by enacting laws that would enhance sharing of information through banks. Counterparty risk is rated highly as it seeks to assure project lenders of the financial standing of the developer. Country or political risk raise the question of a country's ability to service external debt on time. Political risk presents a negative effect and raises the cost of equity for investors evoking consequences that include expropriation or worse still, cancelation of the project. In terms of implementing a project on time, these risks oversee the effect that interest rates have on loans obtained from multinational companies and are used by proprietors during the development process. Low interest rates are an advantage to investors in accelerating construction activities on projects while higher ones have the opposite effect. With high interest rates, developers slow down on their projects. The literature reviewed noted two research gaps relating to methods used in implementing PPP schemes as well as monitoring systems needed to mitigate risks on projects.

4. Research methodology

A mixed method research methodology was used for the study included structured interviews as well as administration of an industry wide questionnaire. 11 specialists were selected from a list of individuals that had crafted the PPP law. Experience, therefore, was the criteria used for those chosen on the focus group. The emphasis of the interviews was to establish evaluation and monitoring methods. Further, 120 questionnaires were administered to various construction industry professionals. However, out of the 53 questionnaires that were completed, 5 contained errors in the answers given by respondents. These were rejected with the final analysis for the paper based on 47 responses. As risk is perceived to make project assessment uncertain, Spearman's rho was used to assess the accuracy of evaluation and monitoring methods. The interviews and questionnaire distribution were done in Lusaka.

5. Focus group interview information and analysis

Owing to the fact that PPPs were novel in Zambia at the time of the study, a purposive sample of 11 stakeholder interviewees were selected based on their knowledge of the PPP procurement mode. Descriptive analysis was used to interpret the collected qualitative data (Silverman, 2010). Responses on the monitoring methods were further analysed using Spearman's rho. Respondents interviewed in held high and middle management positions in their organisations. All the respondents had a minimum of a bachelor's degree. However, three had post graduate master's degrees. 8 of the respondents had well over 15 years of experience in the construction industry while 3 had only served for 10 years. 72.72% of the respondents had PPP experience while 27.28% had not. However, respondent's PPP experience was limited to responding to requests for proposals and submission of the same to client organisations. Only one chief executive had gone beyond submission in terms of advising clients over implementation procedures. This was a response of less than 10% (9.09%).

5.1 Financial evaluation tools and analysis

A total number of 6 financial evaluation tools were identified as shown in **Table 1** below. These were:

Table 1: Financial evaluation tools

	Evaluation tool	Responses	% response
1	Financial appraisals	5	45.50%
2	Cash flow analysis	2	18.18%
3	Profit and loss analysis	1	9.08%
4	Development concept	1	9.08%
5	Cost benefit analysis	1	9.08%
6	Life cycle costing	1	9.08%
	Totals	11	100%
	% response	100%	

Financial appraisals were the preferred monitoring tool by financial institutions as noted by eight respondents (giving a response of 80%). This was followed by cash flow analysis that had two (20%) occurrences from respondents. It was observed that projects applied a combination of decision-making tools. Hence a combination of the use of financial appraisals and cash flow analysis was noted twice (for A and B). The other monitoring tools used were profit and loss analysis, development concept, cost/benefit analysis and life cycle costing which had a single response each, as listed above. However, such tools are very basic in examining the financial worthiness of PPP projects. Such tools are vague in assisting proper risk assessment of projects.

5.3 Spearman's rho financial evaluation tools method accuracy

Spearman's rho calculations were used to determine the accuracy of use for project evaluation of five of the financial monitoring tools recommended by the focus group. The five financial monitoring tools were the payback period of the project, internal rate of return, life cycle costing, discounted cash flow and net present value. Typically, these are the tools used for evaluating the financial management of projects. Spearman's rho gives the relative strength of a relationship. The resultant assessment between 0 and 1 indicates no direct construal. However, when the rho value is squared, a proportional reduction in error (PRE) in the tools is conceivable. The given equation for obtaining the desired rho value was (Healey, 2009):

$$r_s = 1 - \frac{6\sum D^2}{N(N^2-1)} \quad [1]$$

where N is the ranking of the tool and D^2 is the sum of differences in the ranks of the groups

Table 2: Spearman's rho calculation for financial evaluation tools

Financial evaluation tools	Mean	Field mean ranking	Focus group rating	Focus group ranking	D	D^2
Payback period	4.30	1	5	1.5	-0.5	0.25
Internal rate of return	3.98	2.5	4	3	-0.5	0.25
Life cycle costing	3.98	2.5	3	4.5	-2	4
Discounted cash flow	3.74	4	3	4.5	-0.5	0.25
Net present value	3.62	5	5	1.5	3.5	12.25
					$\sum D^2 = 0$	$\sum D^2 = 17$

Spearman's rho value=0.15

Using the formula shown above [1], a Spearman's rho value of 0.15 was obtained. By squaring 0.15, the value of 0.0225 was obtained meaning the use of the financial evaluation tools with risk assessment imbedded in them, would have a predictable reduction in error of 2.25%. This means using financial evaluation tools would have an accuracy rate of about 97.75%, minimizing errors by 2.25%. Financial tools that are able to analyse a compendium of time-related risk factors such as inflation, political threats and global influences. The challenge of having accurate financial projections is an assurance to both developers as well as recipients of the scheme, guaranteeing timely successful completion.

6. Analysis of the industry questionnaire

An industry-wide questionnaire survey was conducted using the earlier structured questions devised for the focus group interviews. These were expanded to gather as much information. Again, the draft questionnaire was pre-tested so as to improve response clarity as well as the removal of ambiguities.

6.1 Survey composition

It was necessary to investigate factors that warranted good project monitoring before, during and after implementation of a scheme. A key component of this was to ascertain whether the construction industry was ready to accept the PPP mode of development. PPP contracts can be complex and that industry professionals may not be able to handle certain technical difficulties. A sample size of 5% of registered firms with the National Council for Construction was taken leading to the distribution of 120 questionnaires and had 53 responses. Of these, 5 had noticeable errors in the answers given by respondents. The remaining 47 responses where used in the analysis obtaining a response rate of 39.17%. Researches of a similar nature done by Jang (2011) and Awodele (2012), gave responses of 53% and 32%, respectively. Response rates from the various professionals consisted of 12 out of 33 quantity surveyors (25.53%); 11 out of 13 valuation surveyors (84.62%); 9 out of architects (36%); 10 out of 28 civil engineers (21.28%) and 6 out of 21 contracting firms (28.57%). All the respondents were in management positions and were well advanced in their careers. The respondent with the highest years of working construction experience had 14 years while the lowest only had a year. 47 years was the average age of the respondents. In terms of education, all stated to have a minimum of a basic degree with at least 14 years' experience while five had a post graduate masters' degree. Results from the questionnaires were analysed qualitatively as well as using Spearman's rho.

6.2 Respondent's PPP experience

Respondents were asked to indicate their industrial experience as well as the period they have dealt with PPPs. There was a huge disparity in terms of the year's worked, industrial experience and PPP proficiency. Noted among the respondents was the low PPP experience. Although 66% (representing 31 respondents) indicated that their organisations had done PPPs, actual working experience on these types of contracts was negligible. 34% (i.e. 16 respondents) indicated that they had never participated in PPP projects.

6.3 PPP monitoring methods and discussion

From **Table 4**, only 31 respondents had participated in PPP contracts. These were asked to indicate what monitoring methods had been used on PPP projects. **Table III** gives the respondent's frequencies and means of their preferred monitoring methods that were listed using a Likert scale of 1 to 5; one indicated 'less preferred' while 5 was the 'most preferred'.

Table 3: Preferred monitoring methods

	Type of monitoring method	Frequency	Mean	% Response
1	Budgeting	25	4.45	81
2	Cash flows	21	4.36	68
3	Profit and loss analysis	17	4.32	55
4	Return on investment analysis	14	4.26	45
5	Life cycle costing	11	4.02	34
6	Sensitivity analysis	9	3.77	29

From Table 5, 81% of the respondents indicated that 'budgeting' was the most preferred method for monitoring PPP projects. This was followed by cash flows (68%); profit and loss analysis (55%); return on investments analysis (45%); life cycle costing (34%); and sensitivity analysis (29%). However, such tools are very basic in monitoring the financial worthiness of PPP projects. For instance, most budgets are done for a limited period of time of one to five years. PPP projects on the other hand exceed 25 years. Budgets were preferred by developers because they showed the profitability of project (Ronnie, 2018). Inevitably, this means that methods of monitoring must be focused on the phases of the projects. Responses from the respondents, however, preferred short term methods (1 to 3) than ones that gave a long term perspective (4 to 6).

6.4 Monitoring methods accuracy

Spearman's rho calculations were used to determine the accuracy of use for project monitoring of the six monitoring tools. The obtained values by using formula [1] yielded 0.58 which when squared gave a proportional reduction in error (PRE) of 3.4%. As the computation suggests, these monitoring methods can achieve an accuracy of 96.6%. This verifies use of financial tools with the proviso that project risks are carefully monitored during the negotiation, construction and operation phases.

Table 4: Monitoring methods

Monitoring tools	Mean	Mean ranking	Group rating	Ranking	D	D²
Budgeting	4.45	1	5	1.5	-0.5	0.25
Cash flows	4.36	2	5	1.5	0.5	0.25
Profit and loss analysis	4.32	3	1	6	-3	9
Return on investment analysis	4.26	4	4	3	1	1
Life cycle costing	4.02	5	2	5	0	0
Sensitivity analysis	3.77	6	3	4	2	4
					$\sum D^2 = 0$	$\sum D^2 = 14.5$

Spearman's rho value = 0.58

Financial monitoring methods have the advantage of constantly ensuring that risks are gauged over the period of the project.

7. Proposed decision support framework for PPP projects

One pertinent issue pointed out in the foregone discussion and analysis of the focus group, questionnaire focused on the lengthy implementation period for PPP projects. There were 17 steps identified in the procedure of Act No. 14 of the PPP law from the proposal of the project to its execution with the process taking a period of one to three years. Cost implications of the procedure were not the ambit of this research project. Decision support, however, must start from before the conceptualisation of the project. The government departments give consent starting with the registration of the concept until the final clearance is given by the Office for Promoting Private Power Investment (OPPPI) in the Ministry of Mines, Energy and Water Development.

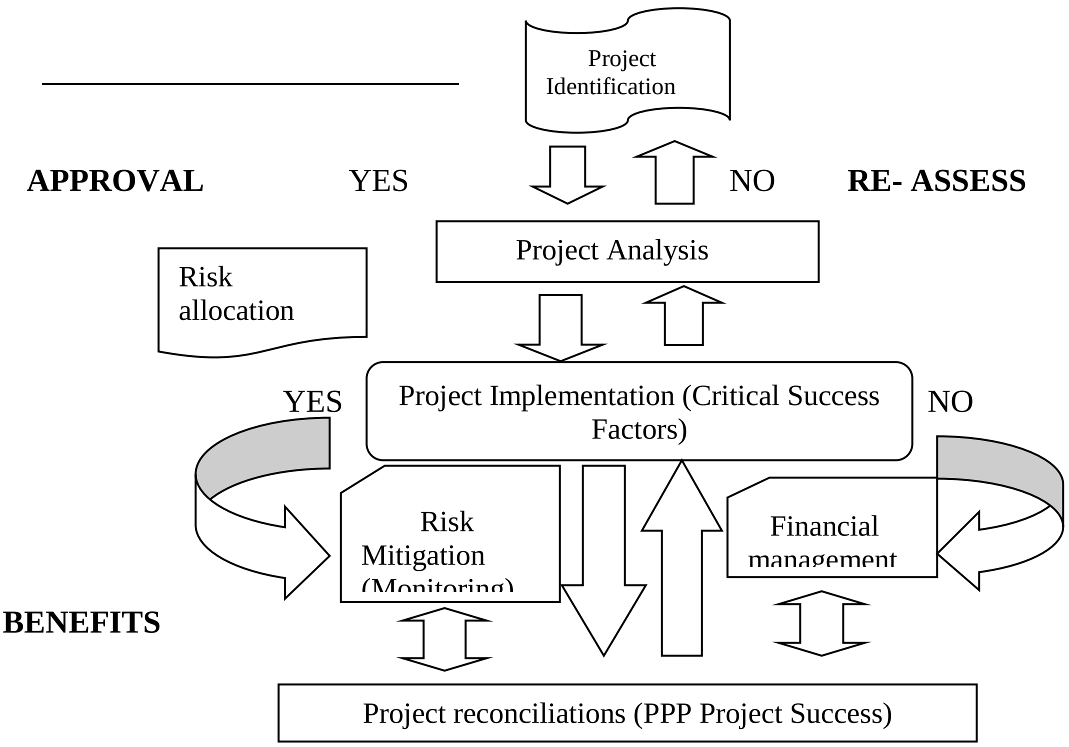


Figure 1: Proposed Decision Support System framework

One pertinent issue pointed out in the foregone discussion and analysis of the focus group, questionnaire focused on the lengthy implementation period for PPP projects. There were 17 steps identified in the procedure of Act No. 14 of the Public- Private Partnership policy (GRZ, 2009) from the proposal of the project to its execution with the process taking a period of one to three years (Mukalula and Muya, 2014). Decision support, however, must start from before the conceptualisation of the project. Government departments give consent starting with the registration of the concept until the final clearance is given by the Office for Promoting Private Power Investment (OPPPI) vested in the Ministry of Mines, Energy and Water Development. A major setback in the current procedure is the difficulty of going back on issues covered. This is not surprising as meetings normally take several months apart. Following up on critical issues pondered at the beginning, are left unattended. Due to time, financial structuring issues are overtaken by inflation that make projects attain supplementary budgets.

The proposed decision support system took into consideration the key element of time i.e. from the moment the project is proposed to its implementation. In order to achieve greater value for money (or benefits), allocated risks must constantly be aligned to critical success factors in order for the project to succeed (Cui et al, 2018). For this to happen, stringent project analysis must be done. Project specific risks must be evaluated. If at these critical stages, there would be a mis-alignment of the risks envisaged, then the entire project must be re-assessed. Financial management is an important aspect in re-assessing the project's financial viability amid known and unknown risks (Smith et al, 2014; Heider et al, 2015). Investment is only considered when there would be an adequate return to the investor. Weighted average cost of capital (abbreviated as WACC) is what investors often use to balance their equity and debt which is reflected in analyses concerning the profit and loss analysis as well as return on investment. Essentially, corporate investment is negatively related to the cost of capital. Lower interest rates in developing countries encourages investment. The Zambian banking situation has had high interest rates which have hindered investment in key sectors such as energy and road construction. Companies that vying for investment have a duty to have their risk profiles equated to the WACC so as to cover project threats (Balog et al, 2017). Project threats would then be handled by the best party to handle them in the PPP contract (Joslin and Konchitchki, 2018).

The focus group was again approached to critique the decision support framework for PPP implementation in Zambia. Various suggestions were given that aided changing of some aspects to the framework. Eventually, 8 out of the 11 individuals consulted, were able to verify the workability of the framework shown in Figure I. This gave a 72.73% response in favour of the use of the framework.

8. Conclusions

The following conclusions were drawn from the findings of the study:

(1) respondents were well able to articulate issues on PPP monitoring in spite of the fact that PPPs have been recently introduced in Zambia;
(2) respondents preferred a combination of financial tools in monitoring PPP projects such as financial appraisals with cash flow analysis and development concept with profit and loss analysis since these have the capability of assessing the weighted average cost of capital (WACC);
(3) financial evaluation methods such as profit and loss analysis, cash flow analysis, financial appraisals and were better able to analyse long term risks in projects using the capital asset pricing model (CAPM);
(4) respondents used financial monitoring tools for PPP projects with the most used being budgeting and the least being sensitivity analysis; and
(5) financial monitoring tools have a high accuracy rate in monitoring projects.

9. Recommendations

In the southern African region, South Africa is leading in the use of PPPs as a mode for development. Botswana and Namibia have also instituted laws in using PPPs and are still in their infancy. This study have shown the grave challenges for countries convinced that PPPs are a remedy to lack of development. The following recommendations have, therefore, been made with a view that corrective measures would be taken to ensure the successful implementation of projects. These are:

(1) that construction industry professionals be trained in risk related financial disciplines to assist them in evaluation processes; and

(2) that short- and long-term monitoring methods be adopted during implementation.

10. Limitations and scope of the research

The following limitations from the findings are worth noting in view of the scope of the research:

(1) there was biasness in the responses to the questions in the country wide questionnaire. The majority of the responses leaned towards the acceptance of PPPs without substantive justification for that position;

(2) data on critical success factors was not discussed in the findings; and

(3) there was perceived misunderstanding of concepts related to monitoring procedures, risk allocation and mitigation among professionals that answered the questionnaire. For instance, quantity surveyors' perceptions were largely driven to ensure that PPP prior quantitative aspects be monitored before the project is embarked on. Architects thought that clients needed to get on with projects irrespective of being financially able. There is need to examine the impact of this array of perceptions before PPPs projects are implemented.

Acknowledgements

The authors acknowledge the support from the Copperbelt University for supporting the research regarding the effect of risk allocation in the Zambian construction industry.

References

Abednego, M. P & Ogunlana, S. O (2006, June). Good Project Governance for better Public Private Partnerships. *Proceedings of the 13th Annual European Real Estate Society Conference* (Vol 13, p. 8-15).

Alfen, H, Jan, Y, Kalidindi, S.N & Singh, B (2009). An Introduction to the PPP Concept in Public Private Partnership. Infrastructure Development, 23 (6/7), 112 -130.

Awodele, O. A. (2012). Framework for Managing Risk in Privately Financed Market Projects in Nigeria, Edinburgh: Heriot-Watt University, (Chapter 3)

Balog, D, Batyi, T.L, Csoka, O & Pinter, M (2017) Properties and comparison of risk capital allocation methods, European Journal of Operational Research, 259 (2), 614-625.

Belkhir, M, Boubakri, N & Grira, J (2017). Political risk and the cost of capital, Emerging Markets Review, Vol. 33, 155 – 172

Bull, B. & McNeill, D (2007). Development Issues in Global Governance – Public Private Partnership multilateralism. (1st ed.). Abingdon: Taylor and Francis-Routledge, (Chapter 3).

Cui, C, Liu, Y, Hope, A, & Wang, J (2018). Review of studies on the public-private partnerships (PPP) for infrastructure projects, International Journal of Project Management, Vol. 36 (7), 773 – 794

Davies, W. E & Giovannetti, E (2018). Signaling experience and reciprocity to temper asymmetric information in crowdfunding evidence from 10,000 projects. Technological Forecasting and Social change, 133, 118-131.

Government of the Republic of Zambia (2009). Public-Private Partnership Policy and the Act. Lusaka: Government Printers. (Chapter 6).

Healey, J F (2013). The Essentials of Statistics – A tool for Social research. (3rd ed.). Wadsworth: USA, (Chapter 2 and 12).

Heider, F., Hoerova, M., & Holthausen, C (2015). Liquidity hoarding and interbank market rates: The role of the counter party risk. Journal of Financial Economics, 118 (2), 336 – 354.

Jang, S.G (2011) A Concessionaire Decision Model Development and Application for the PPP project procurement. Sheffield, UK.

Joslin, S & Konchitchki K (2018) Interest rate volatility, the yield curve and macro economy. Journal of Financial Economics, 128, 344 - 362

Kartashova, K (2018) Improving public equity markets? No pain, no gain, Economic Letters, Vol. 162, January, pp. 69 – 72

Mukalula, P. M & Muya, M. (2014, November). The challenges of implementing public private partnerships – decision-making framework for Zambia. In proceedings of the 3rd Construction Management Conference (ISBN: 978-1-920176-99-0, p.25)

Mukela, M. (2006, May). The significant other – a case of public private partnerships in Zambia. In conference proceedings of the National Council for Construction conference on public private partnerships. (p.10)

Silverman, D. (2010). Doing Qualitative research. (3rd ed.). London: Sage, (Chapter 3).

Smith, N.J, Merna, T., & Jobling, P., (2014). Managing risk in construction projects. (3rd ed.). Chichester: Wiley-Blackwell, (Chapter 9)

Yescombe, E. R (2007). Public Private Partnerships: Principles of Policy and Finance. (1st ed.) Burlington: Elsevier Limited, (Chapter 7).

Zulu, S., & Muleya, F. (2009, August). Delivering infrastructure Development using PPP/PFI: A challenge for Zambia. In proceedings of the Association of Schools of Construction in Southern Africa. (Vol 2, p.56)

Construction workers' preference and acceptance of digital data provision on the construction site

Dujuan Yang[1,*], Bauke de Vries[1] and Laurens van der Schaft[1]
[1]Information Systems in the Built Environment, Eindhoven University of Technology
[*]email: d.yang@tue.nl

Abstract

The architect, engineering, and construction industry (AEC) are adapting their ways of working, by replacing the paper-based communication through digital information, such as the Building Information Model (BIM). The data provision is an essential aspect of BIM adaptation. This research investigated the obstacles of such adoption and explored the impacts of variated data provision variables and attributes on construction workers' preference and acceptance. A stated choice experiment design and discrete choice modeling were applied. An expert interview and an initial questionnaire were conducted to gain knowledge about the important attributes and levels which may have impacts on construction workers' communication on site. In addition, the initial questionnaire also captured the construction workers' awareness of different digital interfaces and data formats, general understanding of new ways of working, and their motivations for adoption if any. Based on the interview and the initial questionnaire results, a stated choice experiment was designed. The experiment focused on the adoption regarding the different format of communication. In total, 178 respondents from the construction sector were recruited in the Netherlands between June - Sep 2018. After cleaning the data, finally, 156 valid questionnaires were used for analysis. Mixed logit (ML) model has been applied for estimations. From the estimation of the stated choice experiment, it can be concluded that construction workers prefer a digital interface over a paper. Important attributes which increase the likelihood of digital data provision to be chosen are the tablet size, interface, and level of integration. From these results, we can conclude that construction workers are in general willing to accept more innovative data formats. Therefore, current prejudges in the industry as conservatism is not accurate, at least in the Netherlands.

Keywords: Construction workers, Stated choice experiment, Data provision, Construction site

1. Introduction

In contrast with many other industries, the construction sector has limited innovations regarding the way of working during the last decades (Styhre, 2011). With the rapid development of ICT tools, new ways of working are emerging. Building information modeling (BIM), which is one of the most promising technologies and a new way of working, allows improving the efficiency in architect, engineering, and construction industry (Liu, Xie, Tivendal, & Liu, 2015). BIM was initially set up for designers to reduce design errors and to improve communication with other stakeholders. The concept of BIM also presents the excellent potential for the construction sector for improving the workflow on the construction site (Svalestuen, Knotten, Laedre, & Professor, 2017). The traditional form of data provision on site (2D on paper) is not effective in handling the work complexity and the number of actors (Bryde, Broquetas, & Volm, 2013; van Berlo & Natrop, 2014). Davies & Harty (2013) argued that data provision could be more efficient and by bringing BIM onto the construction site, which can also contribute to the prevention of errors (Davies & Harty, 2013). As widely acknowledged in the literature that the information used on the construction site is not up to date (Harstad, LÃ¦dre, Svalestuen, & Skhmot, 2015; Ibrahim, Krawczyk, & Schipporiet, 2004; Mäki & Kerosuo, 2015). A server-based system such as BIM is able to handle last minutes changes from stakeholders, such as client and contractor and deal with external factors efficiently (Bargstädt, 2015; Ibrahim et al., 2004). Moreover, BIM provides a much richer information source comparing to paper. Many researchers argued that the communication based on both visual information and data linked information is the most effective way (Liu et al., 2015; Svalestuen et al., 2017).

There is a substantial amount of research have studied the benefits of implementing BIM on site, the BIM technology itself, and ways of implementation of BIM. However, this body of research focusses mostly on possible applications of BIM tools, methods, and workflows, not on the readiness of construction workers and the extent to which this can be implemented (Eastman, 2008; Hardin, 2009). To be more specific, they did not address the implementation readiness from the user point of view (Bryde et al., 2013). A few case studies have been conducted recently, in which specific applications have been monitored (Moum, Koch, & Haugen, 2009; Ruwanpura, Hewage, & Silva, 2012). However, these case studies evaluate one specific way of adopting BIM on the construction site. They did not explore the preference of site workers or compare their preferences between new methods of working. Moreover, there is no consensus in which way or which solutions should be adopted (Mäki & Kerosuo, 2015).

Therefore, in this research, we will explore whether construction workers are willing to work with digital formats and which forms of data provision are preferred by the current generation of construction workers on site by implementing a stated choice experiment in the Netherlands. The remaining of the paper is organized as follows. The second section explains in details about the stated choice experiment design and data collection. It is followed by the model explanation and estimation results in section 3. The paper is finalized with a conclusion and discussion.

2. Experiment design and data collection

2.1 Stated choice experiment design

A stated choice experiment design is used to systematically vary data provision attributes, and capture the construction worker's preference regarding different forms of data provision. As shown in the book of Hensher et al. (2015), the design includes two main steps, which are selecting related attributes and levels, and designing choice profiles (Hensher, Rose, & Greene, 2015). In this research, related attributes and levels are collected and defined based on existing technologies and initial interviews with innovation managers, BIM managers, and construction supervisors. In total, ten attributes with two levels each were selected to describe the different data provision format of paper or digital. Detailed information is shown in Table 1.

Table 1: Selected attributes and levels

	Attributes	*Explanation*	*Levels*
Paper	*Data format*	*This can be either 2D or 3D, 2D means you can see the width and the length of an object on a drawing. 3D means you can also see the height*	*2D*
			3D
	Size canvas	*Size canvas is based on paper sizes. A3 is the double size, and A0 is the standard large foldable drawing.*	*A3*
			A0
	Integration drawings	*It indicates the level of information, in which a low level only shows one profession and a high level also shows the relevant information of other professions to prevent clashes between professions.*	*Low*
			Normal
	Speed to accessing	*How fast you can get updated information.*	*5 min*
			15 min
	Updating speed	*The speed of a change will be updated.*	*2 weeks*
			4 weeks
Digital	*Data format*	*This can be either 2D or 3D. 2D means you can see the width and the length of an object on a drawing. 3D means you can also see the height*	*2D*
			3D
	Size canvas	*Two digital interfaces are used on construction sites which are tablets and large size screens; which are approximately a size of A4 and A2. Moreover, the A2 sized screens would usually be attached to a wall (in the construction site office) or mounted in an information booth.*	*A4*
			A2 (fixed screen)
	Integration drawings	*Integration drawings indicate the level of information, in which a low level only shows one profession and a high level also shows the relevant information of other professions to prevent clashes between professions.*	*Normal*
			High
	Speed of accessing	*How fast you can get updated information.*	*1 min*
			5 min
	Updating speed	*The speed of a change will be updated.*	*3 days*
			1 week

A full factorial factor design was applied for the labeled experiment, which includes all possible combinations of the 10 attributes with 2 levels each. In total, 2^10 = 1024 different profiles were generated. To reduce the number of profiles, an orthogonal fractional factor design was used. It selected a subset of 12 profiles that show zero correlation, which was estimated in the SAS software. The selected profiles were systematically varied in 12 choice sets. Each choice set consists of two labeled data provision profiles and the "none of these" option. To further reduce the burden on respondents, the 12 choice sets were blocked into 2 blocks of 6 choice sets each. For each respondent, the 6 choice sets from one randomly selected block were presented.

The stated choice experiment design was set together with context variables since some attributes of data provision may be more preferred in certain activities on the construction site. Four main tasks are identified with the intention to capture the differences, which are structural work, finishing work, reporting flaws, and filling out checklist/forms. Construction workers were requested to choose the data provision alternative they like best under the situation of conducting a certain type of activities on site. They can also choose the "none of above". Figure 1 provides an example of a choice set.

"Please, read the descriptions in the table carefully and choose the column which you find most suitable to your preference, for the ***Finishing work****."*

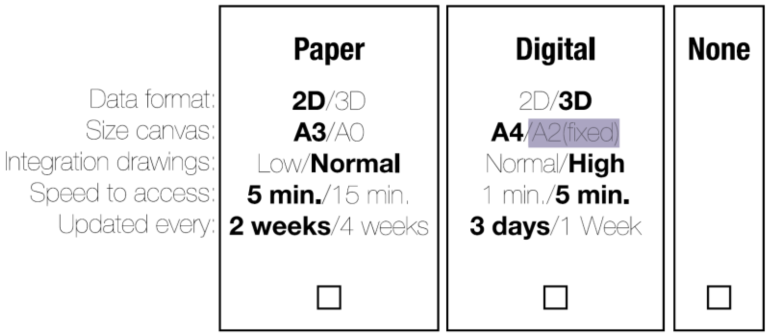


Figure 1: An example of a choice set

In addition to the stated choice experiment, socio-demographic information and attitude towards technology readiness were collected. A selection of ten questions from technology readiness index, which was developed by Parasuraman (2000) has been asked (Parasuraman, 2000).

The questionnaire was implemented in the Bergênquete system, which is a web-based questionnaire system developed by the Eindhoven University of Technology. A six-minutes instruction video was included at the beginning of the questionnaire. The introduction video includes a short explanation of why this research was conducted, how to fill out the questionnaire, and more elaborately explainations of the variables. The presentation was recorded both in English and Dutch. It provideed sufficient information for respondents to fill the questionnaire by themselves.

2.2 Data collection and descriptive analysis

The data collection was collaborated with the company named TBI contracting , which is a big construction company in the Netherlands, and companies from the TBI holding. After getting permission at the management level, it was allowed to get contact information of the construction workers and able to conduct the data collection on site. For on-site data collection, we gathered respondents from construction site group by group to avoid disruption of their work. For each group, around five random respondents were invited to join the data collection. It took around 6 minutes for introduction, and approximately ten minutes for filling the questionnaire. The questionnaire was filled by either personal smartphones or provided tablets. To increase the number of respondents, we also asked the foreman to send the request for completing the questionnaire by email or via Whatsapp.

In total, 178 respondents have filled the questionnaire. Out of 178, 151 respondents have completed the questionnaire correctly. Five respondents have completed the first two parts of the questionnaire, which is sufficient for this research. Twenty-two respondents have missing values due to the technical issues of the questionnaire system, which has been removed for the data analysis. Finally, 156 respondents were used for analysis for this research.

The distribution of age groups is shown in Figure 2. Based on the age distribution of TBI, our data sample under-represents the age group 55-65 and over-represents the age group 40-45 and 15-20. As shown in the data that the majority of the employees is above 45 years old. This can be explained by the last economic crisis and a growing number of freelancers. Recruiting or keeping new employees is difficult for construction companies, which cause a lack of young employees. The current profession and years of work experience in the current profession are shown in Figure 3. Majority of workers are carpenter and stone mason. Besides, there are workers from the Mechanics, Electrical engineers and Plumbers (MEP), and managers. The manager consists of (assistant) site managers and foremen. It shows that a large percentage of the respondents remains in their current profession for a long time. The highest attained level of education was asked as well. The results show that majority has attained either the level of pre-vocational secondary education (43%), intermediate vocational education (8%), or secondary vocational education (41%). 4% of them has complete higher professional education, which are project supervisors and site managers. Only 4% of them have attained primary education.

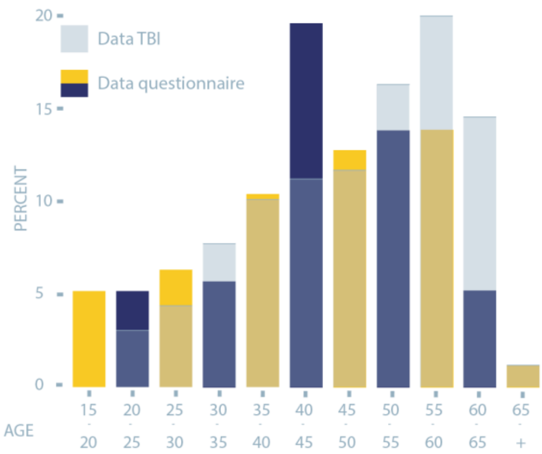


Figure 2: Age distribution of respondents compared to the age distribution of TBI

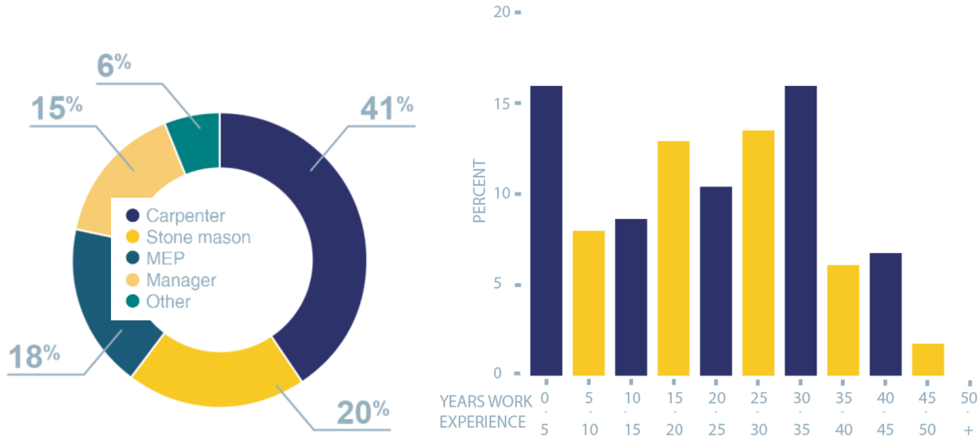


Figure 3: Current profession and years of work experience

3. Model and Results

3.1. Multinomial logit model (MNL) and Mixed logit model (ML)

Discrete choice models are widely used for predicting the acceptance of new technologies or decisions for choosing one alternative from a finite set of mutually exclusive alternatives. It can determine the influence of various attributes with different levels in people's decision making (Ben-Akiva & Bierlaire, 1999; For et al., 2006). The estimated parameters are used to interpret the impacts of certain attributes or attributes' level on people's preference. It can be based on random utility theory, which assumes that each individual selects the option, which is economic rationally and utility maximization(Kløjgaard *et al.*, 2012). The utility is described in equation (1).

$$\mathrm{U}_{ij} = \alpha_{ij} + \beta_j'^{A} \mathrm{X}_{ij}^{A} + \varepsilon_{ij} \quad (1)$$

Where U_{ij} is the utility of alternative j for individual i, α_{ij} is the alternative specific vector, X_{ij}^{A} is a (A×1) vector of the attributes of alternative j. It includes the variables of data format, size canvas, integration drawings, speed of accessing, and updating speed. The (1×A) vector $\beta_j'^{A}$ is the associated parameters. ε_{ij} is a random term that is IID distributed across choice alternatives. The probability of alternative j be chosen is shown in equation (2). This is the basic format of MNL model.

$$\mathrm{Prob}\big(\mathrm{U}_{ij} > \mathrm{U}_{ip}\big) = \frac{\exp\,(\alpha_{ij}+\beta_i'^{A}\mathrm{X}_{ij}^{A})}{\sum_{q=1}^{J_i}\exp\,(\alpha_{qi}+\beta_i'^{A}\mathrm{X}_{qi}^{A})} \tag{2}$$

Considering the digital form of communication is relatively new products, and the preference may differ in terms of personality and attitudes towards new technologies. Therefore, it is better to take into consideration the preference heterogeneity in a mixed logit model. It accounts for the unobserved heterogeneity among populations and relaxes the restrictive independence of IIA assumption of the MNL model. The random effects of the main variables was considered. The random effects across individuals are assumed to be independent and identically distributed. We assume that they follow a normal distribution. Therefore the utility function (1) can be extended to (3), where $\beta_{ki}'^{A} = \beta_k + \sigma_k v_{ik}$. β_k is the population mean, v_{ik} is the individual specific heterogeneity, with mean zero and standard deviation one, and σ_k is the standard deviation of the distribution around β_k. The choice specific constants α_{ij}, and the elements of β_i are distributed randomly across individual with fixed means (Revelt & Train, 1998).

$$\mathrm{U}_{ij} = \alpha_{ij} + (\beta_k'^{A} + \sigma_k v_{ik})\mathrm{X}_{ij}^{A} + \varepsilon_{ij} = V_{ij} + \varepsilon_{ij} \tag{3}$$

The probability for an alternative will be chosen based on the utility maximization. We assume that people will select the alternative which has the highest utility, which is the same as MNL model. The probability of alternative *j* be chosen is shown in equation (4)

$$\mathrm{Prob}\big(\mathrm{U}_{ij} > \mathrm{U}_{ip}\big) = \frac{\exp\,(V_{ij})}{\sum_{q=1}^{J_n}\exp\,(V_{ij})} \tag{4}$$

3.2. Results

Both the MNL and the ML models were applied for model estimation. The adjusted rho-square was used to evaluate model performance. The results show that the ML model performance (0.27) is much better than the MNL model (0.14). It indicates significant improvements by including the heterogeneity. The detailed results are shown in table 1. The column Pr(>|z|) refers to the two-tailed p-values testing the null hypothesis that the coefficient is equal to zero. 0.05 has been used as the value to judge whether there is a significant effect. Due to the page limitation, only significant results from the ML model are explained.

For the alternative option of paper, the coefficients for data format 2D was positively significant at 10 percent. It means that construction workers are more likely to choose paper if it is shown in a 2D format. For the digital way of data provision, they were more likely to choose it once the canvas size is A4, and the integration drawings level is normal. It means that they prefer an easy carry digital format with a lower extent of relevant information from other professions. For socio-demographic variables, the results show that for the digital alternative, the workers from the sectors of residential & utility and others were less likely to choose digital data provision format comparing to other sectors. The workers who were profession stone mason and MEP were less likely to choose the digital data provision, whereas managers were more likely to choose digital comparing to carpenters. The coefficients of age showed that the worker who is between 25-35 years old preferred the digital alternative comparing to the age cohort of 15-25. The results of innovativeness proved our assumption that the more innovative worker were more likely to accept digital data provision. For the tasks impacts, the results showed that for reporting flaws tasks, workers had a significant preference to the digital interface.

For the standard deviation parameters, the results showed that all attributes have significant variations except for the low integration drawings of the paper. Most standard deviations are rather large compared to the means values which indicate that preferences of the respondents were diverse.

Table 2: Results of MNL and ML model for data provision

Alternative	Attribute	Level	MNL		ML	
			coefficients	Pr(>|z|)	coefficients	Pr(>|z|)
Paper	Data format	2D	0,103	0,495	0,789.	0,092
		3D	-0,103		-0,789	
	Size canvas	A3	0,162	0,282	0,373	0,379
		A0	-0,162		-0,373	
	Integration drawings	Low	-0,109	0,474	0,187	0,656
		Normal	0,109		-0,187	
	Speed to access	5 Minutes	-0,103	0,495	-0,230	0,583
		15 Minutes	0,103		0,230	
	Updated every	2 Weeks	0,051	0,736	-0,070	0,866
		4 Weeks	-0,051		0,070	
Digital	Data format	2D	0,158	0,281	0,192	0,689
		3D	-0,158		-0,192	
	Size canvas	A4	0,156	0,287	1,098*	0,040
		A2 (fixed)	-0,156		-1,098	
	Integration drawings	Normal	0,236	0,114	1,345*	0,029
		High	-0,236		-1,345	
	Speed to access	1 Minute	-0,043	0,772	-0,460	0,386
		5 Minutes	0,043		0,460	
	Updated every	3 Days	-0,115	0,431	-0,807	0,149
		7 Days	0,115		0,807	
Socio-demographic variables & attitudes						
Digital	Constant		1,333**	0,006	2,820	0,107
	Company	Residential	2,705		6,970	
		Installation	-0,096	0,802	1,217	0,344
		Residential & utility	-0,888***	0,000	-2,724***	0,001
		Other	-1,721***	0,006	-5,463***	0,001
	Current profession	Carpenter	0,538		3,089	
		Stone mason	-0,486.	0,056	-1,472	0,074
		MEP	-0,383	0,300	-3,293*	0,015
		Manager	0,620*	0,044	2,687*	0,016
		Other	-0,290	0,474	-1,011	0,473
	Work experience	0 - 5 years	0,744		1,911	
		5 – 15 years	0,022	0,952	-0,616	0,670
		15 – 30 years	0,007	0,987	0,069	0,967
		30 + years	-0,772.	0,079	-1,364	0,431
	Age	15 – 25 year	-1,422		-8,334	
		25 – 35 year	0,871*	0,041	5,142*	0,004
		35 – 45 year	-0,145	0,720	0,729	0,652
		45 -55 year	0,030	0,944	0,549	0,752
		55 + year	0,666	0,198	1,914	0,313
	Innovativeness	0 – 2.5 score	-1,459**	0,001	-4,002***	0,000
		2,5 – 3,0 score	-0,292	0,288	-0,282	0,768
		3,0 – 3,5 score	-0,711**	0,006	-2,418**	0,006
		3,5 – 4,0 score	-0,513	0,054	-1,927.	0,038
		4,0 + score	2,976		8,629	
	Tasks	Structural work	-0,650		-2,939	
		Finishing work	-0,345	0,182	-0,480	0,577
		Reporting flaws	0,776**	0,007	1,178.	0,062
		Check-lists/forms	0,219	0,252	2,241**	0,002
None	Constant		-4,513**	0,000	-6,150*	0,049
	Company	Residential	2,897		4,149	
		Installation	-0,492	0,496	0,617	0,762
		Residential & utility	-0,870.	0,099	-1,720	0,272
		Other	-1,535.	0,068	-3,046	0,404

	Current profession	Carpenter	-0,834		-3,710	
		Stone mason	-0,076	0,871	0,846	0,311
		MEP	-1,080	0,220	-2,365	0,295
		Manager	0,711	0,245	2,979	0,174
		Other	1,278	0,140	2,251	0,449
	Work experience	0 - 5 years	5,317		7,621	
		5 – 15 years	-0,804	0,214	-3,271	0,205
		15 – 30 years	-2,463***	0,001	-2,534	0,367
		30 + years	-2,049*	0,011	-1,816	0,436
	Age	15 – 25 year	-12,623		-15,001	
		25 – 35 year	2,726**	0,007	3,497	0,342
		35 – 45 year	2,708**	0,006	3,354	0,310
		45 -55 year	3,326**	0,001	3,445	0,316
		55 + year	3,864***	0,001	4,705	0,217
	Innovativeness	0 – 2.5 score	2,067*	0,014	1,715	0,213
		2,5 – 3,0 score	0,673	0,453	0,880	0,562
		3,0 – 3,5 score	1,578.	0,052	1,190	0,371
		3,5 – 4,0 score	1,266	0,130	1,155	0,327
		4,0 + score	-5,584		-4,940	
	Tasks	Structural work	-0,799		-3,432	
		Finishing work	0,211	0,659	1,123	0,336
		Reporting flaws	0,362	0,354	0,498	0,578
		Check-lists/forms	0,227	0,552	1,811*	0,035
Standard deviations for ML model						
Paper	Data format	2D			2,077**	0,004
	Size canvas	A3			1,431*	0,021
	Integration drawings	Low			0,059	0,944
	Speed to access	5 Minutes			1,670*	0,012
	Updated every	2 Weeks			1,846**	0,004
Digital	Data format	2D			-2,728**	0,001
	Size canvas	A4			3,737**	0,002
	Integration drawings	Normal			6,368***	0,000
	Speed to access	1 Minute			3,369**	0,002
	Updated every	3 Days			3,406***	0,000

4. Conclusion and discussion

Many studies have explored new technologies implementation in the construction site. In these studies, they have proved the usability of these new technologies by case studies. However, very limited knowledge has gained so far regarding the construction workers' acceptance of innovative technologies or data provision formats such as tablets, BIM-booths, information screens, and Augmented and Virtual reality. The core difference regarding data format is digital versus paper. Therefore, in this study, we summarised the main attributes based on existing technologies for digital data provision and designed a stated choice experiment to formulate trade-off points for digital and paper data provision formats. Both MNL and ML models have been used for model estimation with 165 respondents' data from the construction site. The results show that construction workers prefer a digital interface. However, there is heterogeneity existed in the population. The attributes such as tablet size and level of integration of the drawings have impacts on their preference. Although in the literature, the speed of access is identified as an important attribute (Bargstadt, 2015; Berlo & Natrop, 2014; Ibrahin et al., 2004), the results did not show a significant variation among construction workers. Moreover, the preference also depends on their socio-demographic status and technology innovativeness attitudes. The innovativeness defined by the Technology readiness index of Parasuraman (2000) is in line with the expectations.

The main outcomes are controversial with the literature, which indicated the construction sector is very conservative, and the construction workers are reluctant to innovate (Harstad et al., 2015). The results of this study show a progressive mindset of construction workers. They are more likely to accept a digital interface over the paper, and the majority is not reluctant to choose for an innovation. A possible explanation might be the adoption of the technologies situation is based on their familiar environment, which creates more trust. There also might be a misunderstanding between construction managers and construction workers on site. The underestimation of construction workers' acceptance and abilities might contribute to the perception of conservatism in the construction sector.

References

Bargstädt, H.-J. (2015). Challenges of BIM for Construction Site Operations. *Procedia Engineering*, *117*, 52–59. doi:10.1016/J.PROENG.2015.08.123

Ben-Akiva, M., & Bierlaire, M. (1999). *Discrete choice methods and their applications to short term travel decisions*. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.40.8438&rep=rep1&type=pdf

Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of Building Information Modelling (BIM). *International Journal of Project Management*, *31*(7), 971–980. doi:10.1016/J.IJPROMAN.2012.12.001

Davies, R., & Harty, C. (2013). Implementing 'Site BIM': A case study of ICT innovation on a large hospital project. *Automation in Construction*, *30*, 15–24. doi:10.1016/J.AUTCON.2012.11.024

Eastman, C. M. (2008). *BIM Handbook : a guide to building information modeling for owners, managers, designers, engineers, and contractors*. Wiley. Retrieved from https://www.academia.edu/3183272/BIM_handbook_A_guide_to_building_information_modeling_for_owners_managers_designers_engineers_and_contractors

For, P., Koppelman, F. S., Bhat, C., Sethi, V., Subramanian, S., Bernardin, V., & Zhang, J. (2006). *Koppelman and Bhat A Self Instructing Course in Mode Choice Modeling: Multinomial and Nested Logit Models*. Retrieved from http://www.caee.utexas.edu/prof/bhat/courses/lm_draft_060131final-060630.pdf

Hardin, B. (2009). *BIM and construction management : proven tools, methods, and workflows*.

Harstad, E., LÃ¦dre, O., Svalestuen, F., & Skhmot, N. (2015). How Tablets Can Improve Communication in Construction Projects. *23rd Annual Conference of the International Group for Lean Construction*, (July), 391–401. Retrieved from http://iglc.net/Papers/Details/1192/pdf%0Ahttp://iglc.net/Papers/Details/1192

Hensher, D. A., Rose, J. M., & Greene, W. H. (2015). *Applied choice analysis*. Retrieved from https://www.cambridge.org/nl/academic/subjects/economics/econometrics-statistics-and-mathematical-economics/applied-choice-analysis-2nd-edition?format=PB&isbn=9781107465923

Ibrahim, M. M., Krawczyk, R. J., & Schipporiet, G. (2004). A web-based Approach to transferring architectural information to the construction site based on the BIM object concept. *Caadria 2004*, (February), 1–9.

Liu, S., Xie, B., Tivendal, L., & Liu, C. (2015). Critical Barriers to BIM Implementation in the AEC Industry Article in International Journal of Marketing Studies · November. *International Journal of Marketing Studies*, *7*(6). doi:10.5539/ijms.v7n6p162

Mäki, T., & Kerosuo, H. (2015). Construction Management and Economics Site managers' daily work and the uses of building information modelling in construction site management Site managers' daily work and the uses of building information modelling in construction site management. doi:10.1080/01446193.2015.1028953

Moum, A., Koch, C., & Haugen, T. I. (2009). What did you learn from practice today? Exploring experiences from a Danish R&D effort in digital construction. *Advanced Engineering Informatics*, *23*(3), 229–242. doi:10.1016/J.AEI.2008.08.002

Parasuraman, A. (2000). Technology Readiness Index (Tri). *Journal of Service Research*, *2*(4), 307–320. doi:10.1177/109467050024001

Revelt, D., & Train, K. (1998). Mixed Logit with Repeated Choices: Households' Choices of Appliance Efficiency Level. *Review of Economics and Statistics*, *80*(4), 647–657. doi:10.1162/003465398557735

Ruwanpura, J. Y., Hewage, K. N., & Silva, L. P. (2012). Evolution of the i-Booth© onsite information management kiosk. *Automation in Construction*, *21*, 52–63. doi:10.1016/J.AUTCON.2011.05.012

Styhre, A. (2011). In the circuit of credibility: construction workers and the norms of 'a good job'. *Construction Management and Economics*, *29*(2), 199–209. doi:10.1080/01446193.2010.526623

Svalestuen, F., Knotten, V., Laedre, O., & Professor, A. (2017). *Using building information model (BIM) devices to improve information flow and collaboration on construction sites* (Vol. 22). Retrieved from http://www.itcon.org/2017/11

van Berlo, L., & Natrop, M. (2014). BIM on the construction site: Generating on demand, task specific drawings in the site office. *EWork and EBusiness in Architecture, Engineering and Construction*, 63–68. doi:10.1201/b17396-14

Kløjgaard, M. E., Bech, M., & Søgaard, R. (2012). Designing a Stated Choice Experiment: The Value of a Qualitative Process. Journal of Choice Modelling, 1-18.

Creating Information Delivery Specifications using Linked Data

Léon van Berlo[1*] Peter Willems[1] and Pieter Pauwels[2]
[1]Netherlands organisation for applied scientific research TNO
[2]Ghent University, Dept. of Architecture and Urban Planning
* email: leon.vanberlo@tno.nl

Abstract

The use of Building Information Management (BIM) has become mainstream in many countries. Exchanging data in open standards like the Industry Foundation Classes (IFC) is seen as the only workable solution for collaboration. To define information needs for collaboration, many organizations are now documenting what kind of data they need for their purposes. Currently practitioners define their requirements often a) in a format that cannot be read by a computer; b) by creating their own definitions that are not shared. This paper proposes a bottom up solution for the definition of new building concepts a property. The authors have created a prototype implementation and will elaborate on the capturing of information specifications in the future.

Keywords: BIM, mvd, IFC, model checking, information delivery specification

1. Introduction

The use of Building Information Management (BIM) has become mainstream in many countries. Using BIM processes and tools, stakeholders in the Architecture, Engineering, and Construction (AEC) industry are able to model, design and engineer buildings and infrastructure in information-rich 3D models [Borrmann et al., 2018, Eastman et al., 2008, Sacks et al., 2018]. Further-more, they are able to exchange the associated information and achieve less error-prone and more efficient processes in the design and construction of assets in the built environment (buildings, bridges, etc.).

When using an open and neutral information exchange approach in this industry, the exchange of data is recommended to be modelled in Information Delivery Manuals [1][2] (IDMs), which specify Information Requirements (IRs) and Exchange Requirements (ERs) in Business Process Modelling Notation (BPMN)diagrams, text, and tables. These IDMs include specific exchanges, defined as Model View Definitions[3](MVDs). MVDs essentially represent what information needs to be delivered, when, and between which stakeholders.

The Industry Foundation Classes[4](IFC) serve as the de-facto industry standard for representing building information in a neutral format [ISO, 2013]. IFC is hence often recommended as a data format for the data representation of the information needs (what information) in an MVD. In other words, MVDs ideally represent a subset schema of the complete IFC schema in their purpose of defining exchanges (information needs).

This standardized way of working, starting from IDMs, is adopted in many countries, and definitely also in the Netherlands and Belgium. In practice, this often results in a PDF document that

[1] http://idm.buildingsmart.org
[2] https://technical.buildingsmart.org/resources/information-delivery-manual
[3] https://technical.buildingsmart.org/standards/mvd
[4] https://technical.buildingsmart.org/standards/ifc/

specifies the IDM. These IDMs often have different names, resulting in BIM Execution Plans, protocols, Delivery Manuals, and so forth, often depending on regions, languages, countries and local habits.

Yet, the main idea behind the IDM standard is often implemented in practice. Unfortunately, these IDMs seldom include tightly scoped MVDs, as specified in the original IDM and MVD standards, and they definitely seldom go in detail in terms of defining information needs with the IFC data model. Instead, most practitioners reside to defining (required) property sets with specific naming conventions for re-use within a project in a much more manual and ad-hoc manner. As a result, there is an overwhelming number of different properties and products defined within each project adopting an IDM workflow, leading to confusion and people lost in translation across projects.

This article looks into this situation and investigates to what extent the current situation may be addressed by the use of linked data technologies. Recently emerging linked data [Berners-Lee, 2006, Bizer et al., 2009, Heath and Bizer, 2011] and/or semantic web technologies [Berners-Lee et al., 2001, Domingue et al., 2011] enable decentralized information management over the web, and therefore, they might facilitate the bottom up definition and re-use of property sets over project borders. With linked data initiatives in the AEC industry aiming to make building concepts available in a modular, machine-readable, and decentralized fashion [Pan et al., 2004, Rezgui et al., 2011, Curry et al., 2013, Törmä, 2013,König et al., 2013, Pauwels, 2014, Pauwels et al., 2017, Rasmussen et al., 2018, Rasmussen et al., 2017], some of the aforementioned issues may be addressed using a linked data approach for the creation of information delivery specifications, which is the purpose of research reported in this article.

In Section 2, we provide a review of how MVDs and IDMs are specified in the Netherlands, thereby documenting the use of the 'BIM Base IDS' in practice. This section looks specifically in how diverse IDS documents are built, project per project. This leads to a number of identified issues in the process of creating IDMs and then requirements that should be met by any solution aiming to create IDMs. In Section 3, we document a state of the art review of technologies used in the creation of IDMs, including PDF, Object Type Libraries (OTLs), the buildingSMART Data Dictionary (bSDD), and Linked Building Data (LBD). Section 4 and 5 propose a solution for the creation of IDMs, including a prototype tool. The paper is finished with Results, Evaluation, Discussion, and Conclusions.

2. BIM Information Delivery Specification

To define information needs for collaboration, many organizations are now documenting what kind of data they need for their purposes. The 'Coordination View' is the most used MVD used in practice [van Berlo, 2019]. The Coordination View is very complex, and covers most of the 2x3 version of the full IFC schema. In practice, many of the mandatory elements are not modelled and therefore not available in the exported IFC data-set from authoring tools. This causes problems during coordination of a project, because information that project partners need, is missing in the data. To deal with this problem,13 contractors and buildingSMART Benelux started an initiative to create an MVD to deal with the most common basic elements of information exchange for coordination in IFC.

2.1 The BIM Base IDS

The 'Basic Information Delivery Manual' [5] (Base IDS) provides a solid base with basic requirements that are almost always necessary. Instead of including multiple smaller exchanges in individual MVDs, one main basic minimal MVD is thus provided by this Base IDS. At the time of writing, the Base IDS is adopted by hundreds of organizations and translated in almost 20 languages. The original Dutch title is 'BIM Base/Basic Information Delivery Specification'. During the translation, the current English term 'BIM Basic Information Delivery Manual' is used. During this translation two things happened:

1) The `Information Delivery Specification' was translated to `Information Delivery Manual'. Yet,

[5] https://www.bimloket.nl/BIMbasicIDM

the document is actually much more a Model View Definition then an Information Delivery Manual. The reason for this translation is that the use of Model View Definitions is still quite vague to end users.

2) The term `basis' was translated to `basic', while the Dutch term can also be translated to `base'. The original goal of the document was to create a `base' of requirements that are always in effect for almost every use-case of data exchange. Additional requirements would be built on top of this base. The Dutch term `basis' would have better been translated to `base' in the meaning of `foundation' to build specific information delivery specifications. Part 4.4 was intended to be the gateway to additional project specific requirements.

To represent the ‘BIM Basis ILS’ in a way it was originally intended, we will use the term ’BIM Base IDS’ in this paper.

2.2 BIM Base IDS in practice

Since the launch and successful use of the BIM Base IDS, many organizations have adopted it in their data requirements. Its success sparked the creation of domain specific `Information Delivery Specifications' as well. The Dutch limestone suppliers created a `National Information Delivery Specification for Limestone in the Netherlands'. This limestone IDS was an extension of the BIM Base IDS. Other initiatives have built a specific IDS that conflicts with the requirements from the Base IDS. The authors will not elaborate on these initiatives but like to remark that this could harm the effectiveness and productivity of data exchange in the industry.

The Base IDS is meant as a base, and additional requirements are meant to be built on top of it. At the moment, there are a few issues arising from the use of this approach:

- Issue 1: Most of the additional requirements are defined in unstructured formats (e.g. PDF) or human-readable form with no tools to check data against requirements.
- Issue 2: Comparable requirements, like the capacity of an elevator, are not shared, so there is a welter of equal definitions that are being required in different formats.
- Issue 3: Already existing definitions in other domains (CityGML, gbXML, etc) are being introduced in IFC.

Many extensions to the Base IDS introduce various additional concepts and requirements, often in an unstructured format, and often already existing in other domains. This leads to concepts being defined multiple times, in the worst case in non-machine-readable formats, which in turn leads to confusion, debates and therefore considerable loss of efficiency in the AEC industry.

2.3 Requirements in the creation of an IDS

To tackle the issues identified above, a solution needs to adhere to the following requirements (in order of priority):

1. There is a need to formalize data requirements in a machine-readable way to be able to automate compliance checking;
2. There is a need to make existing building-related concepts and properties available to end users so that they can select and re-use what they need;
3. There is a need to be able to create new building-related concepts and properties when the currently defined are not suitable for the specific case of the end user;
4. There is a strong request to standardize and re-use common building-related concepts and properties in specific domains or regions.
5. There might be a good reason to re-use building-related concepts and properties from other domains (like CityGML, gbXML, etc) to avoid `re-inventing' or copying them into IFC.

These requirements and features will be the benchmark during the review of the current state of the art.

3. Review of current solutions and state of the art

In reviewing the state of the art, we intend to cover mainly the current tools and data models available and/or used for specifying information requirements that are part of an IDM. This includes PDF documents, which is the most commonly used format to represent the IDM itself, and which typically identify lists of custom PropertySets. Furthermore, the buildingSMART realm of IFC, mvdXML, and bSDD is briefly covered. Third and fourth, we discuss the use of Object Type Libraries (OTLs) and Linked Data technologies.

3.1 PDFs and lists of custom PropertySets

Currently the BIM Base IDS, the Information Delivery Specifications built on top of the BIM Base IDS, and the dialect IDS documents are all distributed as PDF documents. This makes the result very accessible for users, and therefore stimulates people to think about their data requirements. However, this approach also provokes fuzzy definitions and uncertainties. Requirements defined this way are also not machine-readable. Automated compliance checking of a data-set against the requirements set in the Base IDS needs a custom made solution every time.

A direct request from users that create Information Delivery Specifications in PDF, was to find a solution to re-use comparable definitions that are needed in different projects. For example, this happened with the definition of the load capacity of an elevator in two projects in the Netherlands. Both projects needed to work with a definition for the load capacity that was different from the standard definitions for *CapacityByWeight* and *CapacityByNumber* as defined in the IFC Schema, and the used BIM authoring tool could not export the IFC data-set with these standardized properties for elevators.

In the first project, the load capacity of an elevator is defined as a property `Capacity' in a separate PropertySet called `Facility Management' linked to the *IfcTransportElement* object. In the second project, the same property, with basically the same semantic meaning is defined as a combination of two separate properties called `Load capacity', in a different custom made PropertySet called `IDS'[6].

3.2 IFC, mvdXML, and bSDD

Using mvdXML, it is possible to define data exchanges in a machine-readably member, thereby picking from what is needed from IFC. Yet, while IFC is the de-facto standard for information exchange in the industry, it does not cover every element that the industry uses. The IFC Schema is focused on defining and standardizing elements that are most commonly being exchanged between different partners in the industry. It can be seen as the largest common denominator for exchange of data in the AEC industry. Yet, specific elements like gypsum board elements are not semantically defined and standardized in IFC, because these have not been identified as elements that need to be in the `largest common denominator' for data exchange.

It was identified that in almost every case, it should be possible to extend the IFC definitions with additional elements for specific cases. There are several ways in which this is currently possible to work with in practice:

1. Using IfcProxyElement
2. Using PropertySets
3. Referring to elements in the bSDD
4. Referring to elements in an external object type library

This paper will not elaborate on the several options. The conclusion of this section is that IFC is the standardized, accepted schema for most common elements, and there are several ways to extend the IFC Schema in practice with elements that are specific for a discipline or a region.

At the moment, buildingSMART is controlling the creation of new objects in the bSDD. It is a top

[6] it was actually named after the name of the building, which is changed for publication purposes.

down process with the intention to control the redundancy of definitions, manage overlap of definitions and check the inheritance structures. Besides the extension of IFC, the buildingSMART Data Dictionary (bSDD) is also used for different purposes. It is seen as a mapping between concepts, to identify objects in the built environment and their specific properties regardless of language.

3.3 Object Type Libraries (OTLs)

Because the definition of concepts and elements has a different meaning per region and discipline, many national organizations have started to create their own `Object Type Libraries' (OTLs). These object type libraries have the same intention as bSDD: to extend the definitions in IFC. In some cases, national object type libraries have a mapping to the bSDD, but in most cases they are separate and external to buildingSMART altogether. There are even cases where the libraries do not use IFC as a reference, but build all concepts from scratch, or based on another national data standard.

Similar to the bSDD, also these object type libraries are often managed in a top down approach. The concepts and properties in these initiatives are governed by a team of people and processes with the intention to create a controllable standard to refer to.

Looking at the requirements for our solution, the bSDD and most object type libraries do not comply with the need to `be able to create new building-related concepts and properties when the currently defined ones are not suitable for the specific case of the end user'. Our solution needs to be more bottom up, with the ability for users to define new concepts and properties that cannot be found in the current libraries.

3.4 Linked Building Data

As indicated in the introduction, linked data technologies are impacting on the AEC industry as a set of technologies that allows to specify vocabularies and data in a much more decentralized manner. The defined data is fully machine-readable, therefore, the linked data technologies might be perfect for addressing the above need(s). Therefore, an OWL version of IFC has been created, aiming to open up the use of these technologies for the AEC industry. As a result, alternative to the EXPRESS schema of IFC, also XML-based and RDF-based serializations of IFC are available, dubbed ifcXML and ifcOWL [Beetz et al., 2005, Pauwels and Terkaj, 2016] respectively.

Suggestions have been made to make the ifcOWL ontology (1) simpler [Mendes de Farias et al., 2015,Pauwels and Roxin, 2016], (2) more modular [Terkaj and Pauwels, 2017], and (3) more easily extensible [Beetz et al., 2014]. Of those three aims (simplicity, modularity, extensibility), one of the more central aims is to make building data available in a modular fashion. Therefore, there is an ambition to make building data available on the web, using modular ontologies that can be combined as wished [Schneider, 2017, Schneider et al., 2018]. This ambition is pushed most predominantly by the W3C LBD CG and closely follows well-known linked data best practices [Lóscio et al., 2016] (see also [Rector, 2003]). This inherently modular approach allows extensibility of the schema by anyone for any purpose. This might be a solution to the bottom up approach that is needed in our solution, and is missing in the current bSDD and known object type libraries.

Of central importance to the current aim to be able to define custom product types and associated properties, is the Ontology for Property Management(OPM), which has been proposed by Rasmussen et al., 2018.This ontology allows to represent properties in general and manage the changes to those properties over time. The same topic has been discussed at length within the W3C LBD CG, under the PROPS topic (e.g. [Bonduel, 2018]). Al-though the W3C LBD CG now does not formally support or acknowledge any Properties (PROPS) or OPM ontology, the overall approach used for representing properties and their management over time, is well-known and informally very well accepted. This overall approach includes a number of ‘levels’. As indicated in Rasmussen et al., 2018, these levels refer to the number of steps/relations between a product and the node (literal or individual)that encodes the value of its property. Listing 1 shows what this means for Level 1, as also explained at length in Rasmussen et al., 2018.

Listing 1: Property Level 1 (adapted from Rasmussen et al 2018)

```
ex:thermalTransmittance a owl:DatatypeProperty .
ex:material a owl:ObjectProperty .
inst:wallA ex:thermalTransmittance "0.27 W/(m2.K)" .
inst:wallA ex:material ex:Concrete .
```

Level 2 and Level 3 properties allow to add more metadata to the property definitions. For example, storing properties in a Level 2 design pattern allows to store units, value, timestamp, author, and so forth, directly with a generic node that represents the property value (see Listing 1). Property definitions in level 3 allow to define even more metadata, which allows the detailed property management with property states and changes over time, which is out of scope here.

Listing 2: Property Level 2 (adapted from Rasmussen et al 2018)

```
ex:thermalTransmittance a owl:ObjectProperty .
ex:material a owl:ObjectProperty .
inst:wallA ex:thermalTransmittance inst:PropertyX .
inst:wallA ex:material inst:PropertyY .
inst:PropertyX ex:value "0.27" .
inst:PropertyX ex:unit "W/(m2.K)" .
inst:PropertyY ex:name "Concrete"@en .
```

The outlined methods for defining properties in Level 1 and Level 2 property definitions can also be used to define the properties and property sets used in information delivery specifications. Essentially, these are generic methods which can also be used in the definition of a bSDD and/or OTLs. A bottom-up approach is also possible. This leads to the following key questions:

- Should properties be defined in Level 1 or 2?
- Where does property (set) naming happen (e.g. thermal transmittance)?
- Are end users able to define their own properties and property sets?

3.5 Conclusions State of the art

The authors conclude that there is no integral solution for end users to define an Information Delivery Specification that adheres to the mentioned requirements (Section 2.3). The current approach to define PDF documents with requirements is not machine readable. The current solutions surrounding object type libraries (and bSDD) are focused on a top down approach. The state of the art in Linked Data has potential, but is still very experimental. Since linked data is the most obvious technology for extending data schemas, in a bottom up approach, with the ability to combine definitions from different domains, this technology is chosen to build a new solution. The fact that these technologies can also be used in the definition of properties and products in the bSDD and in OTLs, makes this approach usable not only in a bottom-up, but also a top-down approach.

4. The proposed solution

Our proposed system to define requirements using a linked data approach consists of two parts:

- A library to create and share property(set) definitions, with a SPARQL [Steve Harris and Andy Seaborne, 2013]and GraphQL[7] interface.
- A tool to combine definitions from IFC, self-created properties and external resources (Section 5). The tool generates SPARQL [Steve Harris and Andy Seaborne, 2013],mvdXML, JSON and PDF [Manola et al., 2015] to share information requirements.

[7] https://graphql.org

4.1 Creating a user IDS

The envisioned use of the solution for creating a user Information Delivery Specification (IDS) is as follows. A user logs into the system. The user decides to define a new IDS. The system suggests some base modules that are popular. These modules consist of a list of required concepts, properties and modelling guidelines. These modules could be those of the `BIM Base IDS', but also base modules like `2nd order space boundaries' or some other requirement modules. The user selects a couple of these modules to start her own IDS.

In the current prototype, when creating a new user defined IDS from selected existing IDS modules, the requirements defined in those modules are copied to the newly created user IDS. In this way, the user can change the contents of the chosen existing modules, without affecting specifications from other users. It has to be discussed to what extent this is desirable, because changes in the imported modules, e.g. the BIM Base IDS might be counter-effective, or conflicts with other requirements might arise.

4.2 Adding required properties to the IDS

After selecting requirements into a new user IDS, a user can add additional requirements.

End users should be able to log in to a system where they can search for already defined properties, user defined properties, and properties in domains other than IFC.

The first prototype of the proposed system will focus on defining Properties for the already available concepts in IFC.

A user can search for properties in a library. This library consists of the buildingSMART PSet properties and available user-defined properties. The list of search results shows known buildingSMART properties at the top, and existing user-defined properties below. User-defined properties are sorted based on popularity, where popularity is defined by the number of times the property definition is used in any user-created IDS. Finding existing property set definitions follows the same process as finding existing properties. Ideally, the system differentiates between property sets that can be extended and property sets that are fixed (e.g. by the IFC schema).

When the user finds an existing (IFC) property, it can be added to the IDS.

Any property needs to be part of a property set. The definition of properties occurs in the Level 1 and Level 2 ontology design patterns that were documented in Section 3.4. In defining her IDS requirements, an end user is able to search for, generate, and store properties and property sets in a library.

When selecting a property that is part of a property set, the user can define what properties of that property set are mandatory or optional in her IDS.

4.3 Defining new properties

When a user cannot find an existing property, a new one can be created. When creating a new property this property can also be set to mandatory or optional in the IDS.

Newly created definitions are defined in a public library. Each newly created property has a specific URI that is related to the user that created it. After generating a new property, it is stored in the library component. The properties and property sets in this library are publicly available through a SPARQL and GraphQL interface, and of course through the IDS generation tool. These properties can be selected to be used in a (user defined) IDS. User created IDSs are stored separately, and only available for the logged in user.

4.4 Using the IDS

After selecting properties and other requirements, the IDS will be saved and linked to the user profile. A user can export the IDS to PDF, mvdXML, SparQL or a self-defined JSON format.

The vision is to be able to load these machine readable formats into BIM Authoring tools, to make sure all information requirements and properties are defined before exporting to IFC. This will help end-users that are modelling BIM data to make sure they comply with the information requirements, and that the IFC export is valid.

Future development could include the ability to select concepts or properties from other domains like gbXML or CityGML. This will enable interoperability over domains. This will complicate the potential feature to load the IDS in authoring tools to create a valid IFC export.

5. The Development

The prototype was developed in several steps:

1. Translating the IFC PSet Definition XML-schema to OWL
2. Converting the IFC PSet Definition XML documents to RDF
3. Harness a SPARQL engine with the generated PSet Definition RDF triples
4. Embed the SPARQL endpoint in a GraphQL interface
5. Develop the IDS definition tool in a web browser application

The next subsections will describe these steps in more detail.

5.1 Translating the IFC PSet Definition XML-schema to OWL

Since the IFC property set definitions are XML documents specified conform an XML schema[8], the first step was to translate the schema into an OWL ontology with equivalent semantics and references to the ifcOWL ontology. The code snippet below shows the OWL class specification of a property set definition[9].

Listing 3: PSet Definition example

```
PSD:PropertySetDef
  rdf:type owl:Class ;
  rdfs:comment "Top node element of PSD."@en ;
  rdfs:label "Property set definition"@en ;
  rdfs:subClassOf owl:Thing ;
  rdfs:subClassOf [
      rdf:type owl:Restriction ;
      owl:allValuesFrom ifc:IfcProduct ;
      owl:onProperty PSD:applicableClass ;
    ] ;
  rdfs:subClassOf [
      rdf:type owl:Restriction ;
      owl:maxCardinality "1"^^xsd:nonNegativeInteger ;
      owl:onProperty PSD:definition ;
    ] ;
  rdfs:subClassOf [
      rdf:type owl:Restriction ;
      owl:maxCardinality "1"^^xsd:nonNegativeInteger ;
      owl:onProperty PSD:name ;
    ] ;
.
```

The information delivery specification entities have been added to this ontology as well to be able to group the required property sets and marking the mandatory properties of those property sets (Figure 1).

[8] http://www.buildingsmart-tech.org/xml/psd/PSD_IFC4.xsd
[9] https://app.informationdeliveryspecification.org/psets/psetdef.ttl

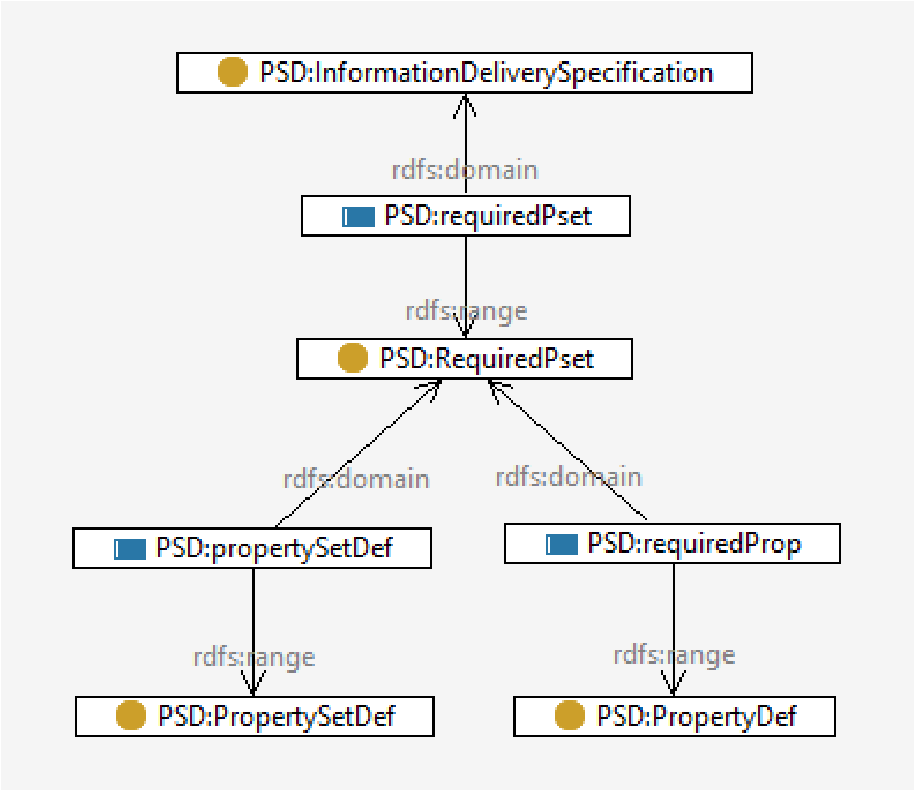


Figure 1: The Information delivery specification ontology

5.2 Converting the IFC PSet Definition XML documents to RDF

In this step, the IFC Pset definitions[10] are serialized to RDF conforming the ontology of the previous subsection. This results in property (set) definitions as displayed in Listing 4 for the BeamCommon PSET example.

Listing 4: PSet BeamCommon example

```
:Pset_BeamCommon
  rdf:type PSD:PropertySetDef ;
  PSD:applicableClass ifc:IfcBeam ;
  PSD:applicableTypeValue "IfcBeam" ;
  PSD:definition "Properties common to the definition of all occurrence and type objects of beam." ;
  PSD:ifcVersion [
      rdf:type PSD:IfcVersion ;
      PSD:version "IFC4" ;
    ] ;
  PSD:name "Pset_BeamCommon" ;
  PSD:propertyDef :p04abf900d1c411e1800000215ad4efdf ;
  PSD:propertyDef :p0970ad00d1c411e1800000215ad4efdf ;
  PSD:propertyDef :p19888c80d1c411e1800000215ad4efdf ;
  PSD:propertyDef :p1ee5d700d1c411e1800000215ad4efdf ;
  PSD:propertyDef :p23aa8b00d1c411e1800000215ad4efdf ;
  PSD:propertyDef :p286f3f00d1c411e1800000215ad4efdf ;
  PSD:propertyDef :p2f964d00d1c411e1800000215ad4efdf ;
  PSD:propertyDef :p33c26a80d1c411e1800000215ad4efdf ;
  PSD:propertyDef :p38871e80d1c411e1800000215ad4efdf .
```

[10] http://www.buildingsmart-tech.org/ifc/IFC4/Add2/html/psd/

5.3 Harness a SPARQL engine with generated Pset Definition RDF triples

Each IFC PropertySet definition is loaded into a triple store as a separate named graph. Named graphs facilitate configuration management especially for the class of custom property set definitions. This RDF triple store forms the public library of properties used by the proposed tool (part 1 defined in Section 4).

5.4 Embed the SPARQL endpoint in a GraphQL interface

Although a SPARQL endpoint is available for querying the properties in the library, many applications rely on alternative means to query for data, such as GraphQL. In this step, a GraphQL interface is added on top of the SPARQL endpoint, thus simplifying the development of web clients. Using GraphQL, a web client can precisely specify its data needs while preventing to receive unnecessary data or, on the other hand, repeatedly has to query for potentially missing data. Figure 2 shows a number of web services that can be executed to receive the necessary data based on GraphQL, e.g. allPSDs, allPDs, searchPD, etc.

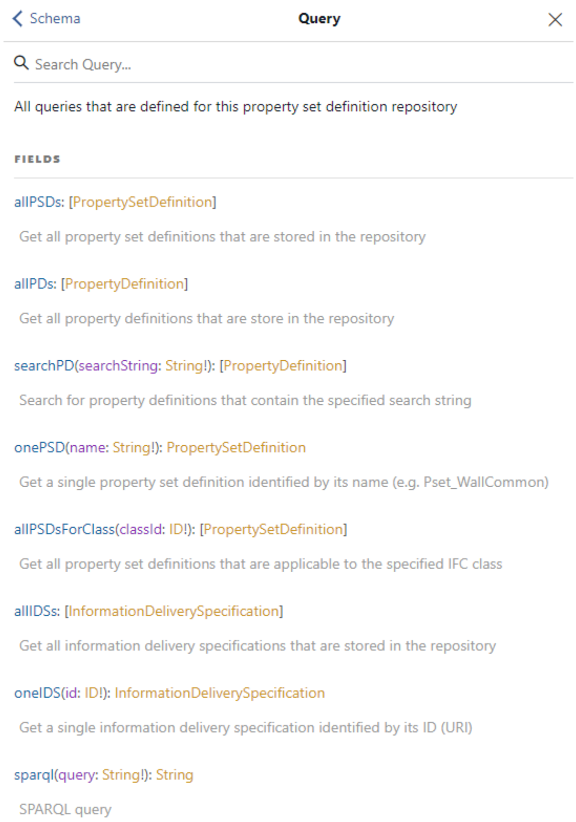


Figure 2: GraphQL query schema

5.5 Develop the IDS definition tool in a web browser application

A web browser application was developed to demonstrate the idea of sharing information delivery specifications that refer to both standard IFC and user defined property sets. Figure 3 shows an example IDS that includes IFC-based property sets only.

Basic information delivery manual

ID

http://openbimstandards.org/information-delivery-specification/Basic_IDM#Basic_IDM

PSET	mandatory properties
Pset_BeamCommon	FireRating, IsExternal, LoadBearing
Pset_ColumnCommon	FireRating, IsExternal, LoadBearing
Pset_DoorCommon	FireRating, IsExternal
Pset_RoofCommon	FireRating, IsExternal, LoadBearing
Pset_SlabCommon	FireRating, IsExternal, LoadBearing
Pset_StairCommon	FireRating, IsExternal, LoadBearing
Pset_WallCommon	FireRating, IsExternal, LoadBearing
Pset_WindowCommon	FireRating, IsExternal

Figure 3: Simple Information delivery manual

6. Results and Evaluation

The result of our work is two-fold: on the one hand, a preset library with properties and property set definitions is available, in the L1 and L2 property definition patterns established within the LBD Community Group. This library mostly covers the properties that are part of the property sets of IFC specifications. Second, a tool is available that allows to re-use existing and define new properties, so they can be used in IDS specifications.

Unfortunately, the tool is not stable enough for full beta testing with end users; only alpha testing (unit tests) has been performed. In addition, the prototype was presented to groups of industry experts, linked building data professionals, and potential end-users. Responses have been enthusiastic and all respondents see the potential. Based on the responses, the authors conclude that the chosen solution approach is one with potential. To fully test the solution, further developments are needed.

In terms of evaluation results, the demonstrations started a debate about the top down definitions of properties and concepts, versus the bottom up approach of the solution. Industry experts that are currently involved in standardization initiatives, are resistant to the bottom up approach of the chosen solution. Linked data experts and end users praise the bottom up approach and see much potential for the solution. Linked data experts focus on the distributed character of the solution. End users focus on the feature that makes it possible to find `the most often used properties in other IDSs'. This feature is only possible because this system centralizes the creation of different Information Delivery Specifications. If the same PSET ontology remains to be used, and the L1 and L2 property definition patterns are maintained as well, it should however be possible to implement the same system in a more distributed manner, including at least a federated query architecture.

During the observations, a big confusion was noticed about the definitions and boundaries of what an IDM and an MVD is, and what an IDS is. This confusion is most likely caused by a lack of knowledge about the definitions of IDMs and MVDs in the buildingSMART context, and a lack of open implementations of both which have a direct impact on the end user. The authors advise that this has to be resolved to facilitate the use of IFC in an effective way in the future, and with our approach, we make an important step forward in bringing MVDs, IDMs, and IDSs to the end user in a practical format.

7. Conclusions

This paper looked into the creation of Information Delivery Specifications (IDSs) in a bottom up and structured format. It hereby investigated the use of linked data technologies for the creation of property set and property definitions. Eventually, a library of those definitions is made available, together with an IDS creation tool which allows the creation of IDSs that include the mentioned property (set) definitions. With these definitions and formally correct IDSs and a referenceable library, a big step forward can be made in the formal specification of work processes and exchanges in the AEC industry.

In our work, we indicated both top-down and bottom-up approaches towards the definition of properties and property sets. The bottom up approach that allows end users to define their own properties is praised as the best way forward by many respondents in our evaluation. The library of newly defined properties is published as linked data and available for everyone to re-use. As such, it can be considered as a public bottom-up data dictionary based on linked data principles and formalisation with SPARQL, JSON, and GraphQL. Publishing the library with a SPARQL and GraphQL interface makes it very accessible.

Because of its bottom-up approach, this solution approach delivers interoperability for the industry without the need for long (top down) standardization procedures, yet it does not stand in the way of top down approaches either. In fact, the tool can be used to collect community feedback on often used and needed properties and property sets, which can inform top-down approaches. As such, the tool is intended to stimulate re-use, and potentially standardize, concepts and properties that are often used in practice.

Acknowledgements

This work was part of the BIM4REN project, which has received funding from the European Union's Horizon2020 Research and Innovation Program under grant agreement No 820773.

References

ISO 16739 - 2013: Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries. Technical report, International Organization for Standardization, Geneva, CH.

Beetz, J., van den Braak, W., Botter, R., Zlatanova, S., and de Laat, R. (2014). Interoperable data models for infrastructural artefacts– a novel IFC extension method using RDF vocabularies exemplified with quay wall structures for harbors. In eWork and eBusiness in Architecture, Engineering and Construction, pages 135–140. CRC Press.

Beetz, J., van Leeuwen, J., and de Vries, B. (2005). An ontology web language notation of the industry foundation classes. In Proceedings of the 22nd CIB W78 Conference on Information Technology in Construction, pages 193–198.

Berlo, L. van (2019). BIM Analytics http://bimsupporters.com (Last Accessed May 2019)

Berners-Lee, T. (2006). Linked data - design issues. http://www.w3.org/DesignIssues/LinkedData.html (Last Accessed 24 Au-gust 2016).

Berners-Lee, T., Hendler, J., and Lassila, O. (2001).The Semantic Web. Scientific American, 284(5):34–43.

Bizer, C., Heath, T., and Berners-Lee, T. (2009). Linked data-the story so far. International journal on Semantic Web and Information Systems, 5(3):1–22.[Bonduel, 2018] Bonduel, M. (2018). Towards a PROPS ontology.

Borrmann, A., König, M., Koch, C., and Beetz, J.(2018).Building Information Modeling:

Technology Foundations and Indus-try Practice. Springer, 1 edition.

Curry, E., O'Donnell, J., Corry, E., Hasan, S., Keane, M., and O'Riain, S. (2013). Linking building data in the cloud: Integrating cross-domain building data using linked data. Advanced Engineering Informatics,27(2):206–219.

Domingue, J., Fensel, D., and Hendler, J. A. (2011).Handbook of semantic web technologies. Springer.

Eastman, C. M., Teicholz, P., Sacks, R., and Liston, K.(2008).BIM handbook: a guide to building information modeling for owners, managers, architects, engineers, contractors, and fabricators. John Wiley &Sons, Hoboken, NJ, USA.

Heath, T. and Bizer, C. (2011). Linked Data: Evolving the Web into a Global Data Space. Synthesis Lectures on the Semantic Web: Theory and Technology, 1(1):1–136.

König, M., Dirnbek, J., and Stankovski, V. (2013). Architecture of an open knowledge base for sustainable buildings based on linked data technologies. Automation in Construction, 35:542–550.

Lóscio, B. F., Burle, C., and Calegari, N. (2016). Data on the web best practices.W3C Working Draft, 19.

Manola, F., Miller, E., and McBride, B. (2015). RDF 1.1 primer, 2014. Working group note, World Wide Web Consortium.

Mendes de Farias, T., Roxin, A., and Nicolle,C. (2015). IfcWoD, semantically adapting IFC model relations into OWLproperties. In Proceedings of the 32nd CIB W78 Conference on Information Technology in Construction.

Pan, J., Anumba, C., and Ren, Z. (2004). Potential application of the semantic web in construction. In Proceedings of the 20th Annual Conference of the Association of Researchers in Construction Management(ARCOM), pages 923–929.

Pauwels, P. (2014). Supporting decision-making in the building life-cycle using linked building data. Buildings, 3:549–579.DOI:10.3390/buildings4030549.

Pauwels, P. and Roxin, A. (2016). SimpleBIM: From full ifcOWL graphs to simplified building graphs. In eWork and eBusiness in Architecture, Engineering and Construction, pages 11–18, Limassol, Cyprus. CRC Press.

Pauwels, P. and Terkaj, W. (2016). EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology. Automation in Construction, 63:100–133.

Pauwels, P., Zhang, S., and Lee, Y.-C. (2017). Semantic web technologies in AEC industry: A literature overview. Automation in Construction, 73:145–165.

Rasmussen, M. H., Lefrancois, M., Bonduel, M., Hviid,C. A., and Karlshøj, J. (2018). OPM: An ontology for describing properties that evolve over time. In 6th Linked Data in Architecture and Construction Workshop (LDAC), CEUR Workshop Proceedings, volume 2159, pages 23–33, UK.

Rasmussen, M. H., Pauwels, P., Hviid, C. A., and Karlshøj, J. (2017). Proposing a Central AEC Ontology That Allows for Do-main Specific Extensions. In Lean and Computing in Construction Congress- Volume 1: Proceedings of the Joint Conference on Computing in Construction, number July, pages 237–244, Edinburgh. Heriot-Watt University.

Rector, A. L. (2003). Modularisation of domain ontologies implemented in description logics and related formalisms including owl. In Proceedings of the 2nd international conference on

Knowledge capture, pages121–128. ACM.

Rezgui, Y., Boddy, S., Wetherill, M., and Cooper, G.(2011). Past, present and future of information and knowledge sharing inthe construction industry: Towards semantic service-based e-construction Computer-Aided Design, 43(5):502–515.

Sacks, R., Lee, C. M. E. G., and Teicholz, P. (2018). BIMhandbook: a guide to building information modeling for owners, managers, architects, engineers, contractors, and fabricators. John Wiley & Sons, Hoboken, NJ, USA, 3 edition.

Schneider, G. F. (2017). Towards aligning domain ontologies with the Building Topology Ontology. In5th Linked Data in Architecture and Construction Workshop, University of Burgundy, Dijon, France.

Schneider, G. F., Rasmussen, M. H., Bonsma, P.,Oraskari, J., and Pauwels, P. (2018). Linked Building Data for Modular Building Information Modelling of a Smart Home. In eWork and eBusiness in Architecture, Engineering and Construction, pages 407–414, Copenhagen, Denmark. CRC Press.

Steve Harris and Andy Seaborne(2013). SPARQL 1.1 Query Language.

Terkaj, W. and Pauwels, P. (2017). A method to generate a modular ifcOWL ontology. In Proceedings of the 8th International Workshop on Formal Ontologies meet Industry, volume 2050 of CEUR Workshop Proceedings, Bolzano, Italy.

CEUR-WS.org. Accessed September 2018.

Törmä, S. (2013). Semantic linking of building information models. Proceedings - 2013 IEEE 7th International Conference on Semantic Computing, ICSC 2013, pages 412–419.

Toward a Data-Driven Architect - A critical investigation into Data-Driven Design and the future of the Architect in the UK.

Allister Lewis
Ayre Chamberlain Gaunt Architects, Belvedere House, Hampshire, RG21 4HG, UK
email: Allister.lewis@acgarchitects.co.uk

Abstract

The introduction of new technologies within the construction industry and requirements to reduce costs, programme duration and carbon emissions has revealed that architects need to understand the opportunities and threats to their profession. This paper captures the emerging concept of data-driven design and how it applies to the role of Architects, using interviews with ten experts in the field of data-driven design. Using a Grounded Theory approach, this investigation critically explores how data-driven design is conceptualised, what skills Architects need in relation to data-driven design, and what impact this may have on the future of the profession.

The outcomes of this research demonstrate that in order to meet future construction industry requirements, Data-driven design requires a reconceptualisation of the Architect profession. The research identifies four alternative futures for Architects; stasis, hybridisation, the loss of Architects to Building Information Management roles, or the emergence of a new profession. It reveals that Data-driven design is changing the way that Architects work, with new skills required to manage and understand data within architectural practice. A model is presented that illustrates how Architects will need to change and adapt fast in a technologically driven construction industry or face marginalisation as a new Data-driven design role emerges.

Keywords: Architect, Building Information Modelling, Data-Driven Design, Computation, Construction

1. Research Problem and Rationale

The construction industry in the United Kingdom (UK) has changed since 2011 due to the introduction of the Government Construction Strategy (Cabinet Office, 2011). The strategy introduced governmental requirements for digital technology to be utilised by the construction industry to reduce costs, increase efficiency and generate better outcomes for government clients. Within this context Architects were required to respond and update their skills to include processes such as Building Information Modelling (BIM). An analysis of further future requirements, such as the Construction 2025 Report (HM Government, 2013) outlines that Architects may be expected to update their skills further to support a reduction in carbon emissions, costs, and timescales. With the growth in global population predicted, pressure on resources and the continuance of climate change, there is a need for Architects to adopt new and innovative practices in the future (Airaksinen, 2016). It has been identified that a minority of Architects have responded to this challenge by developing specialist areas of expertise in software and digital processes – data-driven design. The use of data within their offices and projects, and the use of advanced BIM authoring software, could provide some of the solutions to government requirements and wider construction industry needs. Therefore, an understanding of what data-driven design is within this context and the benefits that it can contribute to the construction industry requires investigation.

2. Aims of this Research

The aim of this research was to understand how some Architects have responded to new digitisation and construction requirements. Furthermore, an understanding of how new technology may affect the role of Architects in the future and how this may support the meeting of the construction industry requirements was investigated. The research aimed to inform future practice and the role that Architects have within this. Three research questions were asked and analysed, see Table 1.

Table 1 Research questions

1.	How do data-driven design specialists conceptualise data-driven design?
2.	What competencies might be required of Architects in the future?
3.	From the perspective of data-driven design specialists, what impact will data-driven design have on the role of Architects?

The future for professions

Susskind and Susskind (2015) highlighted the difficulty in defining what a profession was universally. They discussed that one problem with professions is that they are a small group that provide a service to another relatively small, privileged group. They argued that a greater distribution of expertise, at a reduced cost, should be adopted for the benefit of greater number of people. However, the challenges for professionals is that typically they underperform and Susskind and Susskind (2015) urged for a radical re-evaluation of the ways that they work to resolve this. One of the solutions is the use of technology to support change; *"systems of today are increasingly out-performing human experts, not by copying high-performing people but by exploiting the distinctive capabilities of new technologies, such as massive data-storage capacity and brute-force processing"* (Susskind and Susskind, 2015, p. 45). It appears that Architects would benefit from an awareness of the implied threat to their future position as professionals performing a specific service. How the role of an Architect is conceptualised in the UK, is an area that appears ready to be re-examined.

The Existing Role of Architects

In 2010 the RIBA published a report that examined the future for Architects (Jamieson, 2010). This report identified that changes in the construction industry will alter the context within which Architect's work. The report asked *"who will design our built environment in 2025 and what are the roles required and how well Architectural practice change?"* (Jamieson, 2010, p. 6). As this was prior to the Government Construction Strategy (Cabinet Office, 2011) there was no mention of BIM Level 2 and the Construction 2025 aims or BIM Level 3. However, it identified the title of Architect as being restrictive and that small practices were resistant to integrated technologies, which support BIM methodologies on cost grounds (Jamieson, 2010). The report also raised concerns that senior members of small practices were relying on young people to keep up-to-date and there was a risk of senior staff being deskilled over time. One concerning aspect in the report was; *"Architectural profession unfortunately does not view itself as part of the wider construction industry"*, however they confirmed that this should be changed (Jamieson, 2010, p. 13). It was identified that Architects were reducing in number over time and therefore there was a threat to the influence that Architects have. The report lacks depth regarding future technologies and the requirements for increased sustainability and life-cycle data management, which is a deficiency. One area of concern is that the report promoted; "*practices should concentrate on capital cost savings and not whole life costing, in order to be more persuasive to the client, in this way they are in a better position to raise their fee"* (Jamieson, 2010, p.

34). When set against the priorities that have since followed, this is contrary to the UK Government's BIM Level 2 requirements, particularly Government Soft Landings (BSI, 2015) and the best use of assets and data over the lifecycle and contradicts Susskind and Susskind (2015). Since 2010 there have been several developments that mean this document is now out of date and there is an opportunity to examine the future role of Architects further.

The Future Role of Architects

The decline of the Architect's influence within the construction industry was described by Derbyshire (2014a), who argued that the profession has declined since its peak in the 1960s. Derbyshire (2014) developed this argument and posited a future where innovation and the use of BIM can support a profession that can thrive. Derbyshire argued that part of the solution as; *"BIM and CADCAM (Computer Aided Design/Computer Aided Manufacturing) create the possibility of previously unheard of consumer information, choice and mass customisation of the housing product as never before"* (Derbyshire, 2014). Deutsch (2017a) suggested a profession which is struggling to collaborate and work effectively with other consultants. In addition, he identified communication and collaboration changes that affect speed, cost and quality as important. Deutsch (2017a) identified that using fewer resources, adding innovation and value, and reducing waste was now a standard expectation for Architects from clients but this was difficult to achieve with current work practices.

Deutsch discussed that Architects should reset their role as leaders and "*account for data and information derived from the digital models"* (Deutsch, 2017b, p. 2). Deutsch (2017b) examined the use of data by Architects and how data can support better design decisions and critical thinking could be supported with the use of data rather than stymying creativity. He also discussed how Architects perceive the use of data and how this may be considered a distraction from the core competency of 'design'. Deutsch (2017b) argued that the use of data should enhance craft and increase the speed of decisions and therefore support good design. Deutsch (2017a, p. 94) stated that; *"Being aware of data and understanding of the role of it can and should play in one's practice is very, very important."* Furthermore, Deutsch (2017a) argued that Architects will learn to use data the way that Architects needed to learn how to use pen and trace. Deutsch (2017a) foresees a future where data forms the foundations with which Architects make design decisions. He postulated that design decisions would be made quicker and increase productivity as a result. Deutsch does not confirm where these points originated from or the veracity of them, although many of his observations were based around interviews with practitioners. However, a rigourous research methodology was not communicated and therefore cannot be generalised across the wider industry.

Garber proposed that *"today's digital tools expand, rather than constrain, the authorial and ambit of Architectural design. Architects will have to learn all the rules of the new game to prove him right"* (Garber, 2014, p. 13). Within this context, Garber (2014) discussed that the qualitative design aspects of BIM had been underexplored as these were areas which were not typically linked to cost or more pragmatic requirements. Bernstein (2017) concurs and argued that the value proposition of the Architects contribution to the making of buildings and how digitisation could contribute to this needs re-evaluation. It appears that although technology is being introduced, the issues of retaining design control is a central issue to Architects. If data-driven design can contribute to a greater level of design and creativity this would reveal a valuable contribution to the profession. It would also help Architects to move forward and adopt the technology sooner.

Gauchat (2009) identified that BIM could lead to Architects having either increased importance or increased marginalisation. The requirement to innovate and develop new approaches may test the abilities of Architects and Gauchat (2009) proposed that BIM will be a key aspect of the construction industry in the future. Gauchat (2009) anticipated that companies which were technologically advanced will provide a higher level of service for clients. Gauchat (2009) proposed that education should focus on judgement, teamwork skills, intimate knowledge of design and building delivery. By identifying these skills Gauchat (2009) thought that technology was not the only driver for improvement but better collaborative behaviour of design teams. Ottchen (2009) concurred with this and promoted a *"re-conceptualised from that of romantic genius to technological guru to that of multidisciplinary strategist"* (Ottchen, 2009, p. 25). This investigation illustrated that technological change means that the tools used need to be better understood. The Architect as a team collaborator should be investigated further to understand what this looks like as there are multiple views on how this could be implemented; as a technological approach or as a collaborative team approach.

Data and the Construction Industry

Schwab (2016) proposed that; *"technology and digitization will revolutionize everything"* (Schwab, 2016, p. 14). He explained that digitisation is altering the way that individuals and institutions collaborate and discussed the impact this will have on productivity and the lack of progress thus far (Schwab, 2016). Schwab (2016) identified four impacts of data use on business, one of which was *"products are being enhanced by data, which improves asset productivity"* (Schwab, 2016, p. 54). Schwab (2016) uses the year of 2025 as a benchmark to determine if changes will have occurred in many areas, which would align with the Construction 2025 report timescales (HM Government, 2013). Schwab (2016) highlighted that there was an expectation that the construction industry will change between 2011 to 2025 and indicated that the construction industry workforce will need to be upskilled to be digitally enabled.

Susskind and Susskind (2015) proposed that these changes were early examples of technology bringing about change to a profession, which presented a challenge as well as an opportunity. They proposed that new disciplines and skills were required to manage the use of this data. Susskind and Susskind (2015, p. 303) concluded that in the future *"increasingly capable machines will transform the work of professionals, giving rise to new ways of sharing practical expertise in society"*. They confirm that industrialisation and digitisation will change the landscape and lead professions to be *"replaced by less expert people and high-performing systems"* (Susskind and Susskind, 2015, p. 303). They conclude with a proposal to democratise the access to information and make it widely available for the greater good of society.

Allen (2017) proposed a radical future for architecture that was supported by generative design, software algorithms and robotic construction within the next ten years. Allen (2017) argued that *"Building Information Optimisation"* will be the way forward with computers taking on more of the day-to-day work. Furthermore, he argued that many companies have used traditional BIM as an extension of CAD, and this is limiting progress. Allen (2017) proposed that data may inform design and add information to support problem-solving for Architects. Similarly, Garber (2014) observed new professional models within practice, including; strategic, implementation, consulting and software development units within an organisation, demonstrated by companies such as CASE[1]. Garber (2014) insisted that Architects must understand and utilise the opportunities that arose with change to have a definite creative direction. Garber's work is a useful demonstration of the issues facing the industry with useful examples. However, his approach covers larger practices mainly and niche expert digital design practices. Evidence of the wider effects of how technologies impact on the construction industry are required to be demonstrated. It appears that there is space to develop this in a more quantifiable way and this will be developed within this research to explore how professionals conceptualise data-driven design. Therefore, it is clear that they believed that the introduction of technology will change the role of professionals to a greater extent than has happened in the past and Architects need to consider how this affects them in the future. Within the context of this research project, an assessment of how to achieve this appears pertinent to explore.

Skills of an Architect

An analysis of the skills required by an Architect that relate to data-driven design has revealed that this is a very new area. The RIBA Skills Report (2014) suggested that employers were looking for 'BIM' as a skill, which demonstrated a lack of understanding of BIM as a process, and failed to fully explain what this involved. This report explored a number of skills which were required by architectural practices, including software skills. However, it did not go into detail or mention what these include.

A review of the RIBA Code of Professional Conduct (2005) proposed that Architects should; *"apply high standards of skill, knowledge and care in all their work"* (RIBA, 2005, p. 4). Skills were only mentioned once within this document, and can be compared to a more recent RIBA Student

[1] Now part of the WeWork organisation

Destinations Survey 2017 (MacKinnon, 2017), which illustrated that Information Technology (IT) skills is within the top ten skills required. Again, further definition of what these actually entail was not defined. Young (2015) also mentioned 'BIM' as a skill required of new Architects but failed to define what this actually includes. Therefore, it appears there is room for further definition of what skills are required within the realm of digital design and BIM for Architects.

3. Methods

3.1. Research Type

Grounded Theory is an example of inductive reasoning, and was developed by Glaser and Strauss (Lingard, Albert and Levinson, 2008) to generate theories regarding social phenomena. A bottom up inductive approach supports the use of Grounded Theory as a method that constructs a theoretical analysis based on data, utilising analytical strategies and implicit guidelines for data collection (Charmaz, 2005). It is used to explain a process and uses iterative design to study data collected simultaneously (Lingard, Albert and Levinson, 2008). The data is constantly compared and theories emerge, which are refined over time as new data was introduced. Grounded Theory generates data first and then produces a theory inductively from this. The approach will be selected for the research as it responds to the findings and will ensure theories are developed as the research continues. The advantage of this is that the research will begin with no assumptions on what a data-driven Architect may look like and the enquiry will identify patterns in the data (Cottrell, 2014). Disadvantages to this approach may be the time required, how this is managed and the depth of investigation required. These will be considered as part of the approach and a deadline for data collection established.

3.2. Part 1 Interviews

Interviews with specialists working within the area of data-driven design will be interviewed to understand their approach to the conceptualisation of data-driven design, skills required and how this affects the role of Architects. Reason and Bradbury (2006) confirmed that the risks and benefits from participation should be communicated honestly. They go on to explain that informed consent provides autonomy and privacy. Reason and Bradbury (2006) suggested that a researcher should adopt a relational approach that showed concern for the well-being of the interviewee during the interview and also what happens afterwards. To support this, the researcher will be reflexive to the participants and evaluated responses, this will mean understanding the effect of the researcher at every stage of the research process. The interviews will be synchronous and mirror traditional interview techniques when conducted online. The advantage of this will be real-time responses from interviewees and a high level of involvement from them. Busher (2012) suggested that a disadvantage to synchronous interviews could be that participants fall behind due to a fast pace. To overcome this a limited number of open ended questions will be used (see Appendix 1), progressing at the participants own pace, and ensuring that participants are ready to move on to the next question. Ten interviews will be held until data saturation is reached, for example when participants begin to repeat the same answers to the questions. This means that once the information is being repeated the interviews will conclude.

3.3. Part 2 Thematic Analysis

Nowell et al. (2017) argued that thematic analysis is a qualitative analytical method with the ability to be utilised on a range of epistemological and research areas. It can be used for "*identifying, analyzing, organizing, describing, and reporting themes found within a data set"* (Nowell et al., 2017, p. 2). Thematic analysis provides a very flexible methodology that can be amended depending on the area studied, which can lead to the analysis of deep and rich data. Nowell et al. (2017) argued that thematic analysis can summarise key features of large datasets, however disadvantages can include inconsistencies due to a lack of consistent methods. To overcome this, consistency will be supported by confirming the epistemological position early on, in this case the use of Grounded Theory.

The following process of thematic analysis will be adopted, as recommended by Nowell et al. (2017, p. 4). One-to-one interviews will be held with experts and a set number of questions will be asked of each participant. The questions will explore each participant's role and their understanding of data-driven design. In addition, a question regarding their understanding of the Architect's role within data-driven design will be explored and linked to the design or design process. The opinion of the interviewee will be asked on the future direction of data-driven design and how this influences the role of the Architect and why.

The skills of an Architect will be explored to understand what may be required in the future and this will be linked to their own experiences and how it has assisted them in getting to where they are. Finally, any additional information will be asked of the participants to ensure they had the opportunity to propose additional comments.

3.4. Part 3 Summary Questionnaire

In order to corroborate the data and coding outcomes a summary questionnaire will be issued to enable participants to understand the findings and comment on these. This corroboration of the information was recommended by Nowell et. al (2017). The questionnaire will outline the findings and contain the participant's own transcripts of their interviews for them to comment on the information to ensure they are an accurate representation of the conversation held. In addition to this a feedback form will be included to enable participants to provide commentary on the findings, supporting Nowell et. al's (2017) advice, and ensured that participants have an opportunity to respond to the findings.

4. Results and Analysis

4.1. Introduction

Ten interviews were held with expert participants in the field of data-driven design to uncover knowledge based on the three research questions. These questions will form the structure of this chapter confirming the themes and then returning to the literature to inform the analysis. The outcomes will be summarised in a model to illustrate the findings.

How do data-driven design specialists conceptualise data-driven design?

In order to understand the field of data-driven design, it was important to define what data-driven design was by professionals who were working in this field. This conceptualisation enabled further understanding of this field. Five key themes were identified from the participants and are demonstrated in Figure 1.

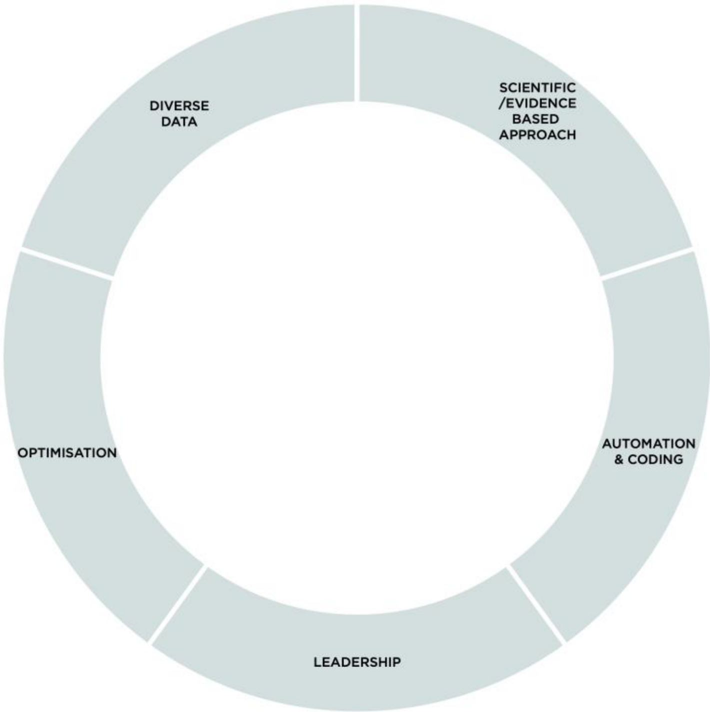


Figure 1: Conceptualisation of data-driven design

Data-Driven Design Conceptualisation Analysis

Question one asked how the participants conceptualised data-driven design. The literature review illustrated a lack of evidence and clarity of what a 'data-driven Architect' will be within the UK in the context of Construction 2025 (HM Government, 2013) report. Furthermore, the diverse nature of the roles of Architects and how they may work, in many different fields, disciplines and sizes of organisation, suggested this wide approach may result in a generalised view, which is not purposive. Deutsch (2017b) conceptualised that data-driven design was something that provided benefits for Architects. However, the detailed conceptualisation of what data-driven design was, appears to have been missed. The themes that have emerged from the research appear to demonstrate that an approach to data by Architects was important and definable. A scientific, evidenced-based approach was considered important to be able to understand data in an objective way, representing a gap in the literature to date. How data is approached, and the methods used to analyse it, were considered important, particularly moving away from a subjective, experiential approach to a more fact-based and scientific, objective approach.

The responses demonstrated that diverse data sources are now being used by participants, departing from traditional modes of analysis. Some of the participants mentioned beginning to use diverse digital data or 'big data' sources to inform their projects, such as social media data linked to a site that was being developed. Also, participants were also relying on their own organisation's historic data to inform projects. Many of the participants discussed the collection and standardisation of their information in a digital way to learn from past mistakes, increase efficiency and speed for future projects. This area could demand further attention to understand how this is recorded, encoded into an understandable or useful format, and shared within the practices they work. Optimisation appeared to be a concern for many of the participants, representing a view that the existing ways of working were inefficient and outdated. The approach to optimisation from the participants considered effectiveness and the ability to produce information faster as essential to meet current needs.

Jamieson (2010, p. 34) illustrated this within the RIBA report; "*practices should concentrate on capital cost savings and not whole life costing, in order to be more persuasive to the client, in this way they are in a better position to raise their fee".* The statement in hindsight contradicts the concept of BIM as a life-cycle approach to a building. Many of the participants directly argued against such an approach and expressed a desire that greater appreciation of the life-cycle should be considered to create more efficient and cost-effective assets. The work of Susskind and Susskind (2015) also discussed a need to understand the future challenges that the Internet and democratisation of data. By driving up fees this will actually reduce access to Architects when they are needed most to help solve societal pressures. It is suggested here that more efficient and automated processes could lead to Architects spending less time on projects and are producing work faster. However, in a profession where fees are relatively low (Jamieson, 2010) it is unlikely that this will be accepted unchallenged as it will go contrary to the ability for Architects to argue they add value. However, in light of future technological change, with greater automation, it should be considered very carefully.

The use of automation and coding to support the process of delivery, design and understanding of large datasets was discussed by many of the participants. The participants commonly suggested that Architects should either understand code, or be able to use coding, so that they can utilise this information for the benefit of a project. Furthermore, the use of automation to support their organisations to be leaders in the market was seen as important to enable a competitive advantage over similar practices. It appears that coding and visual scripting should be incorporated into the Architects future education and start to inform university courses and Continual Professional Development (CPD). Updating the ARB course requirements for certification to ensure properly trained individuals are ready for the future appears pertinent to consider. Schwab (2016) confirmed that *"technology and digitization will revolutionize everything"*. Many of the participants were aligning themselves to take advantage of this in the future.

Participant 7 communicated that Architects have either lost, do not have the power to influence, or are no longer interested in, being leaders within the construction industry. Gauchat (2009) concurred and identified that BIM could lead to Architects elevating their status or could lead to further marginalisation. Furthermore, Deutsch (2017b) concurred and proposed that Architects should re-establish their role as leaders within construction. However, there were different views on how this will be enacted. Will Architects change and morph into something new or the creation of a new discipline entirely? The latter appears to be more likely in view of the participants, due to the perceived entrenched traditional nature of Architects and their inability to change. A new professional role within the construction industry that manages and leads data integration, management and design would disrupt a traditional industry adverse to change.

What competencies might be required of Architects in the future?

An examination of the competencies and skills required was investigated with themes specific to skills and competencies analysed from the text and compiled (see Figure 2) to represent the competencies that data-driven Architects may require in the future.

Figure 2: Question 2 results diagram illustrating new skills required

Architect Competencies Analysis

The competencies required of Architects in the future will be diverse and varied. It appears that some of the competences exist currently and are broadly contained in the ARB criteria. For example, the ARB criteria stated; *"Collaboration in construction and provisions for team working"* (ARB, 2012, p. 14). However, there was no mention of how data or other sources will inform decision-making processes and this appears to be a deficiency. Furthermore, coding skills and research skills are not mentioned as core skills required, suggesting a gap in the criteria, and may reflect why research levels are at a low level within Architects in practice (Miller, 2017). It is recommended as a research finding that this is updated. The RIBA have changed their criteria in the past to reflect modern requirements; in 2015 the charter was updated to promote greater diversity and reduce inequality within the profession (Clark, 2015) and an update to the ARB and RIBA criteria to reflect emerging requirements is possible.

Ottchen (2009, p. 29) proposed that Architects should be; *"re-conceptualised from that of romantic genius to technological guru to that of multidisciplinary strategist"* aligning with the concept of a trusting, sharing collaborator and synthesiser of information and data. This involves the use of softer skills such as communication, negotiation and leadership skills. The Farmer Review (2016) discussed that collaboration was an issue within the construction industry generally, and that successful BIM was predicated on increasing collaboration. Farmer (2016) argued that *'open linked / big data'* use has been lacking and future skills required have not been maximised. Furthermore, he promoted that *'data silos'* should be dismantled for the wider societal benefit. The research has demonstrated that Architects would benefit from challenging existing culture and become lead collaborators integrating design team as well as constructors. The participants stated that Architects were not meeting this challenge currently due to ingrained cultural ways of working and this was limiting the adoption of data-driven strategies across the design team. With the use of more collaborative software, processes, contracts and a more integrated construction industry, these collaboration skills should be understood and enhanced in academia and in practice.

Deutsch (2017a) identified that research was an area that required greater investigation, leading to new specialisms and skills. Many of the participants were actively researching or understood the value of research to develop and enable innovation and new solutions. Research appears to be an area ready for development across the construction industry and the benefits of this could be wide-ranging. How this is shared and communicated will require further research.

The process of delivering a project was not mentioned by the ARB (2012) and many of the participants discussed how they were approaching existing processes and striving to increase the quality of these. Many of the processes discussed within the criteria are purely abstract, such as the 'Planning' process. The delivery of projects, coordination with other consultants, and the production of information is a process that is a critical area for understanding. New methodologies are emerging such as Lean in Construction (Constructing Excellence, 2015), representing one area that appears relevant to be taught. The discussions demonstrated that data conductor or integrator skills will be required for future projects. Furthermore, the concept of coding, data management and automation were not mentioned within the ARB criteria and, as the document was produced in 2011, there is an opportunity to update and contribute new learning outcomes for future students of architecture.

A finding of this research is that the skills required of an Architect appear to need updating to align with the data-driven approach to increase the efficiency and quality of architectural practice. This may result in a new scientific and creative designer integrating data to make new and innovative solutions. Garber (2014) insisted that Architects must understand and utilise the opportunities that arise to have a definite creative direction. Peters (2013) anticipated that computation will augment the intentions of the designer and allow problem-solving skills for complex projects to be increased. Evidence was presented by the participants who communicated that innovative complex problem solver skills will be needed.

From the perspective of data-driven design specialists, what impact will data-driven design have on the role of Architects?

How data-driven design affects the role of Architects and how this may change in the future allowed participants to discuss the current limitations of the role and how traditional practices did not allow the profession to move forward. The four themes that emerged represent future roles that data-driven Architects may fulfil (see Figure 3).

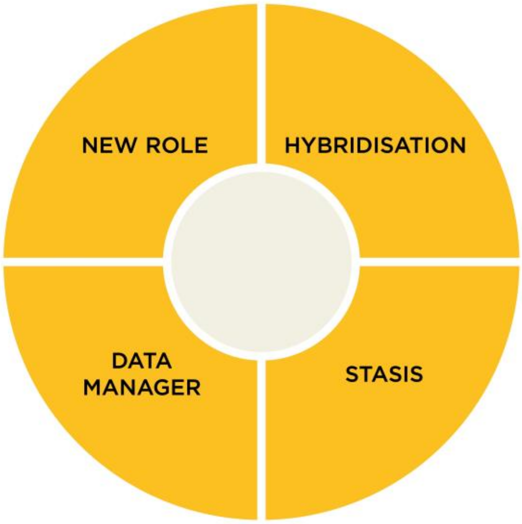


Figure 3: Question 3 results diagram illustrating future role types

Analysis on the Impact of Data-Driven Design on Architects

The impact that data-driven design will have on the role of Architects was discussed by the participants and this aligns with the literature review. Jamieson (2010) proposed that a broader definition of Architect with multiple career paths could be established, responding to the changing nature of the construction industry with different priorities emerging. Similarly, the Construction 2025 (HM Government, 2013) report demonstrated that the future targets are challenges which may require a new type of professional.

The hybridisation of the role to a scientific and artistic one leads to a re-conceptualisation of the role of Architect. If Architects move from a purely artistic and creative role, new specialisations or new approaches will result. A finding of this research is that currently university courses offer architecture as a Bachelor of Arts (BA), however, in the future a more scientific Bachelor of Science (BSc) or hybrid qualification may be needed to ensure future professionals have the correct range of skills. This correlates with the original aims of the RIBA which was established for; *"the purpose of forming an Institution for the general advancement of Civil Architecture, and for promoting and facilitating the acquirement of the knowledge of the various arts and sciences connected therewith"* (RIBA, 2016, p. 2). This original Charter confirms that architecture was invested in the arts and the sciences and also for the furtherance of Civic architecture – one that works for the whole of society. Data-driven design provides an opportunity to rediscover these values for greater societal good and increased standing of the profession. This represents an opportunity for the RIBA to refocus on its core objectives of art and science in architecture, not just good design, and realign itself closer to its core values.

The use of data, the complexity of managing data, and the new skills required suggests that a new data integrator and manager role may be required. This would have an impact on the current role for Architects as they are not trained to understand coding, data, or esoteric programming skills to interrogate this at present. Therefore this data supports Garber (2014, p. 13) who argued that as; *"today's digital tools expand, rather than constrain, the authorial and ambit of Architectural design"*. The participants appeared to agree with this and many were performing this specialist role themselves, usually as a BIM Manager, representing a loss to the profession. It appears that this was a result of projects they were working on requiring detailed support and data management skills which were lacking within the architectural practices they were based.

An area that was mentioned often was a loss of design control for Architects and how technology and data-driven methodologies may affect this. Styhre and Gluch (2009, p. 232) investigated this fear of a loss of creativity within the Architect's role; *"For the Architects, creativity is rather threatened by the day-to-day routines, which gradually and at times unnoticed push the creative activities into the margins of the work, thereby slowly rendering the daily work devoid of the highly praised creative endeavours."* The analysis is very useful as it demonstrates that the focus of design within the role of Architect is not as prevalent as perceived. A finding of this research is that data-driven design should be to automate the mundane, and use what Schwab (2016) discusses as machine learning, to enable greater focus on the design work. This appears to be a key finding of this research, that creativity can be enhanced through automation of standard tasks to enable a focus on creativity and design, not the opposite.

The challenge that Architects experience in their role can be communicated as; stay the same, or adapt, change and adopt data-driven approaches, or change role and become more of a data expert or BIM Manager. Without change in the profession, new professionals will emerge that can harness the data and apply it in a way that is both creative/objective and artistic/scientific, and leave traditional architectural practice.

Models

A model has been presented that links the research questions together to explain the findings (see Figure 4). The model illustrates the four role areas that Architects could develop into as well as combining the data-driven conceptualisation and the competencies that may be required in the future around this. The rings describe the three research questions and the diagram has the Architect profession as central to this and focusses in on the role options available, depending on the level of adoption of data-driven design principles.

The benefits of this model are that it illustrates the research findings in one diagram and allows communication to a wider audience quickly and easily of findings. It also illustrates that the role of Architect is central to the adoption of future skills. For example, an Architect may adopt a hybrid approach and start to understand the data-driven design skills required and then understanding the conceptualisations that underpin this. They will then be in a position to develop as a professional in this area. The model is useful as a framework or roadmap for Architects to understand how specialists in the field of data-driven design understand their skills.

Figure 4: Data-driven design model

A further model has been presented that illustrates the level of potential marginalisation through stasis, and future relevance of the Architect (see Figure 5). The model illustrates that Architects do not appear to be able to remain as existing as they will fall behind Architects which have these skills. The skills are arrayed around the new roles to demonstrate that these will need to be added, in addition to the existing skills that Architects have. However, as discussed there is an opportunity for Architects to move into new roles and the skills are essential if this is to be undertaken.

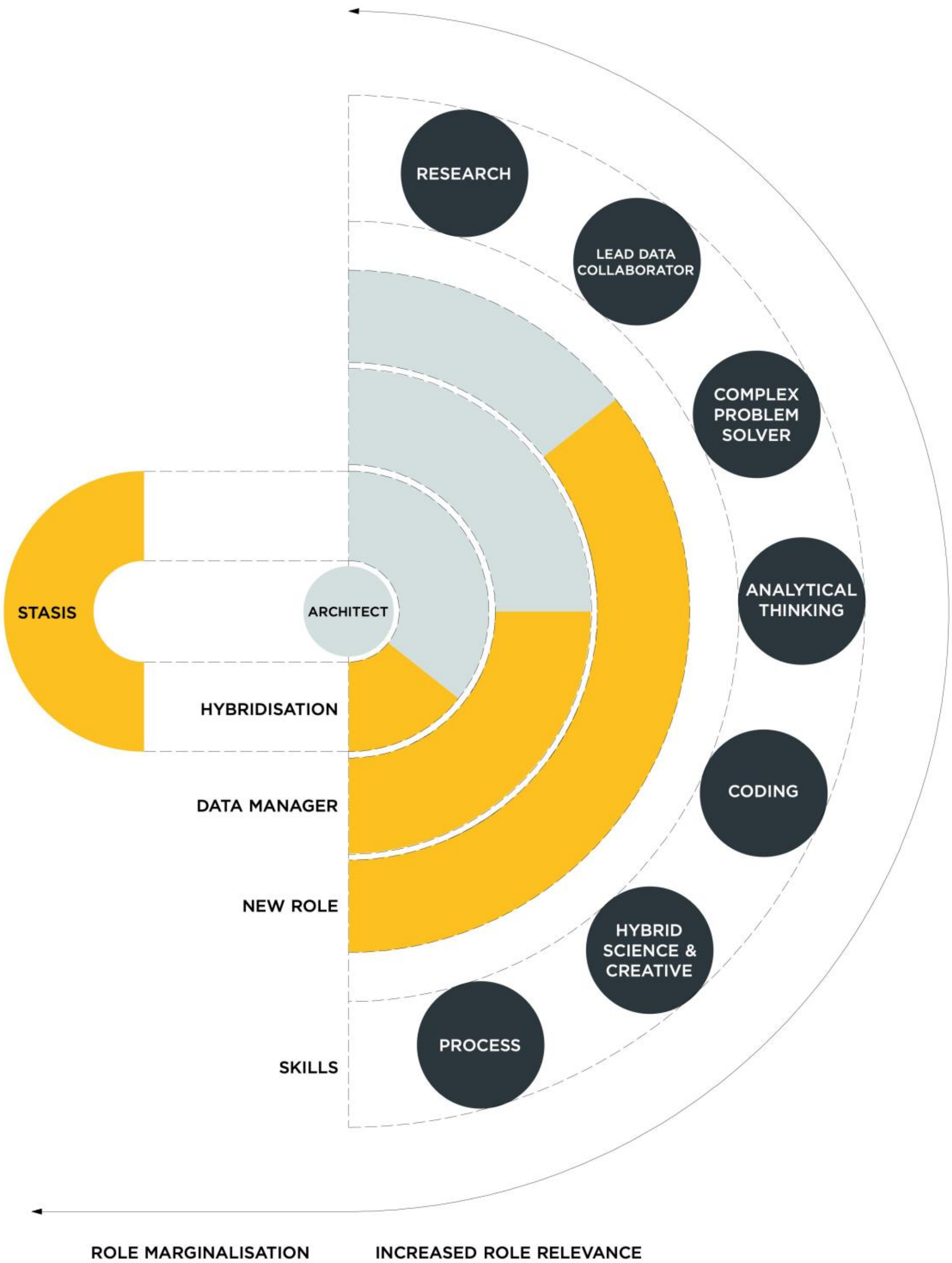


Figure 5: Marginalisation model

The model demonstrates that increased influence within data-driven design is predicated on acquiring the new skills that have been identified. With the greater acquisition the skills will come the increased likelihood of adopting, first hybridisation, then moving into a BIM data manager role and then finally the move to a new role entirely. Fundamentally, stasis is divorced from this process and represents future marginalisation as the profession continues forward meeting future needs without them.

5. Conclusions and Future Work

This research will benefit Architects that are exploring how new technology and processes may impact on their role and skills. Question one explored how data-driven design was conceptualised, with the outcomes demonstrating frustrations with existing ways of working. It was proposed that Architects could benefit by adopting a more scientific approach that utilises diverse data sources, moving away from the traditional practices of experiential and intuition based decision-making. The use of diverse, data sources should allow greater design options to be created based around empirical information. Furthermore, many of the participants expressed a desire for optimisation of the process of delivering a building to increase the automation and speed of delivery. This aligned with the Construction 2025 (HM Government, 2013) aims and objectives and illustrated that the participants are at the forefront of modern problem-solving in their practices. Leadership was seen as a fundamental requirement for Architects which participants felt was lacking. Furthermore, there was a necessity to update existing education criteria from the ARB and also increase data skills for professional continual research and CPD to upskill Architects.

Question two illustrated that new skills are required by Architects to meet existing and future needs. The technology available to Architects now means that there are opportunities for new skills to be adopted. Some of these skills were recognised as already required, such as research and innovation in the construction industry. However, new skills will also be required; data synthesis skills, data informed analytical thinking skills and data management skills. These are new areas that Architects could develop and understand either as a team leader or as a team member utilising them themselves. If these skills are adopted, Architects may become a hybrid profession that is both artistic and scientific in its approach. The creative and design focused approach that Architects have traditionally will be maintained, however this needs to be augmented with data and analytical thinking skills. A hybrid profession would be well placed to meet the needs in the future. Unfortunately, many of the participants discussed that the traditional nature of Architects, with a resistance to change and a fear of new technology, may result in stasis. This suggests there is a risk that this route will not be adopted and lead to fragmentation.

Question three asked what impact will data-driven design have on the future role of Architects? Hybridisation of the architectural role was discussed with the data integrator and data manager role currently being undertaken by Architects who have moved into a BIM Manager role within their organisations which has led to a loss of this particular role to the profession. The last point is the most critical; Will Architects be able to adapt and change or will they remain in their current guise? If the latter is the case then the creation of a new data-driven professional role may be the result and would pose a threat and marginalisation to the existing traditional Architect as they can develop new efficient proposals. A new role would be able to apply data faster and create more effective results as the data will support better decision-making. If Architects are unwilling to change there exists an opportunity for a new role to evolve and become a hybrid which is incorporated into current activities. However, equally there is a risk that non-adoption will result in stasis and the loss of an opportunity to develop and evolve, resulting in stagnation and the inability to respond to future challenges.

Concluding Statement

The research undertaken has demonstrated that data-driven design is an emerging and valid area of architectural practice. It is clear from the results that the impact on the industry could be significant and there is a risk to Architects who do not develop an understanding of data-driven design being unable to fulfil future creative, societal and governmental requirements. The themes that emerged have communicate that Architects in the future will need to be informed by data and also there is an opportunity for new roles and professions to emerge. The major research outcome is that a new role is emerging which is a key research finding and could impact the construction industry at a wider scale. The question of how data-driven practices affect other consultants and practitioners within the construction industry is potentially an important development. It appears that Architects can re-establish themselves as professionals fulfilling the original RIBA Charter aims of a profession focussed on the "*general advancement of Civil Architecture, and for promoting and facilitating the acquirement of the knowledge of the various arts and sciences"* (RIBA, 2016, p. 2). Conversely Architects could face further marginalisation with new roles developing without them.

References

Airaksinen, M. (2016). Research Roadmap Report Smart City Vision. Rotterdam. Available at: http://site.cibworld.nl/dl/publications/CIB Publication 407 (Accessed: 1 August 2017).

ARB (2012). ARB Criteria at Parts 1, 2 and 3. Available at: http://www.arb.org.uk/wp-content/uploads/2017/11/ARB_Criteria.pdf (Accessed: 1 April 2018).

Architect's Registration Board (2017). The Architect's Code: Standards of Professional Conduct and Practice, p. 20.

Bernstein, P. (2017). 'False Binaries', archpaper. Available at: https://archpaper.com/2017/03/phil-bernstein-practice-values-false-binaries/ (Accessed: 6 August 2017).

Clark, T. (2015). Architects welcome RIBA plans to strengthen chartered criteria., Architect's Journal. Available at: https://www.architectsjournal.co.uk/home/architects-welcome-riba-plans-to-strengthen-chartered-criteria/8683850.article (Accessed: 16 March 2018).

Constructing Excellence (2015). Lean Construction, Constructing Excellence. Available at: http://www.constructingexcellence.org.uk/pdf/fact_sheet/lean.pdf (Accessed: 1 April 2018).

Cottrell, S. (2014). Dissertations and Project Reports. London: Palgrave Macmillan.

Derbyshire, B. (2014). A new vision for architecture, Building, February. Available at: http://www.building.co.uk/communities/construction/housing/a-new-vision-for-architecture/5066575.article (Accessed: 20 August 2017).

Deutsch, R. (2017a). Convergence: The Redesign of Design. Chichester: Wiley and Sons.

Deutsch, R. (2017b). Data-Driven Design and Construction. New Jersey: Wiley and Sons.

Farmer, M. (2016). The Farmer Review of the UK Construction Labour Model: Modernise or Die, Construction Leadership Council. London. Available at: http://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2016/10/Farmer-Review.pdf (Accessed: 1 April 2018).

Garber, R. (2014). BIM Design. Chichester: Wiley and Sons.

Gauchat, U. (2009). The $300,000/year architect, Architectural Design, 79(2), pp. 32–37. doi: 10.1002/ad.847.

Jamieson, C. (2010). The Future for Architects, RIBA. Available at: http://www.buildingfutures.org.uk/projects/building-futures/the-future-for-architects/the-future-for-architects-report/ (Accessed: 1 August 2017).

MacKinnon, K. (2017). 'Report - RIBA Student Destinations Survey 2017', RIBA. London. Available at: https://www.architecture.com/-/media/gathercontent/riba-student-destinations-survey/additional-documents/reportribastudentdestinationssurvey2017pdf (Accessed: 1 April

2018).

Miller, N. (2017). Autodesk's BUILD Space Highlights the Need for Research in the Design Community, Architect. Available at: http://www.architectmagazine.com/technology/autodesks-build-space-highlights-the-need-for-research-in-the-design-community_o (Accessed: 4 August 2017).

Nowell, L. S. et al. (2017). Thematic Analysis: Striving to Meet the Trustworthiness Criteria, International Journal of Qualitative Methods, 16(1). doi: 10.1177/1609406917733847.

Ottchen, C. (2009). The Future of Information Modelling and the End of Theory, Architectural Design: Closing the Gap, 79(2), pp. 22–27.

Peters, B. (2013). Computation works: The building of algorithmic thought, Architectural Design, 83(2), pp. 8–15. doi: 10.1002/ad.1545.

Reason, P. and Bradbury, H. (2006). Handbook of Action Research, Participative Inquiry and Practice, London, p. 468. doi: 0432.

Schwab, K. (2016). The Fourth Industrial Revolution. Geneva: World Economic Forum.

Styhre, A. and Gluch, P. (2009). Creativity and its discontents: Professional ideology and creativity in architect work, Creativity and Innovation Management, 18(3), pp. 224–233. doi: 10.1111/j.1467-8691.2009.00513.x.

Susskind, R. and Susskind, D. (2015). The Future of the Professions. Oxford: Oxford University Press.

Young, E. (2015). Fit for purpose? RIBA Journal. Available at: https://www.ribaj.com/intelligence/riba-appointments-skills-survey-report (Accessed: 1 April 2018)

Using real occupancy in retrofit decision-making: Reducing the performance gap in low utilisation higher education buildings

Stephen Oliver[1,*], Saleh, Seyedzadeh[1], Farzad Pour Rahimian[2]
[1]Faculty of Engineering, University of Strathclyde, Glasgow, UK
[2]School of Science Engineering and Design, Teesside University, Middleborough, UK
[*]email:Stephen.oliver@strath.ac.uk

Abstract

The retrofit analysis relies on intuition and faith in the simulations that lead the decision-making process. However, intuition is built upon belief systems which become increasingly unjustifiable as building operation deviates from design whether in utilisation, occupant behaviours or climate. Higher education facilities are known for persistently low but well-recorded occupant presence and density. The low utilisation makes them susceptible to counterintuitive behaviours however, their registration data provides a means of identifying where intuition fails. When operation has little correlation with design it is possible for performance issues to appear to be symptoms of design considerations rather than root cause. Using a discrete space modelled in both EnergyPlus and SBEM as virtual case study g and class registration data, this paper explores how lighting retrofit simulation alludes to heating load concerns resulting from poor envelope and HVAC performance rather than heating management. This is achieved through utilisation of a new approach to scheduling utilisation and BMS systems for higher education facilities in EnergyPlus. The paper concludes suggesting the utilisation modelling method could replace the current heating efficiency credits approach approved for Part L2. Results include discussion on cost-benefit, legislative compliance and implications for retrofit decision-making

Keywords: Retrofit analysis, occupancy, compliance, low utilisation

1. Introduction

Janda (2011) stated "buildings don't use energy: people do" which is not entirely accurate. Building energy is in part consumed to meet the needs of people, but it is also attributable to the beliefs of the designer, building manager and occupants. Whether it is the designers' assumption that operational utilisation will be comparable to design or occupants' subjective perceptions, energy consumption can partially be attributed to assumptions rather than needs. In the case of design assumptions, higher education facilities' utilisation of teaching spaces in the UK is recorded is typically around 27% (Space Management Group, 2008) which is neither represented in compliance models nor meaningfully accommodated by existing utilities, despite utilisation being considered a primary cause of the building performance gap (Hong *et al.*, 2016; Kneifel *et al.*, 2016; Ridley *et al.*, 2014). Occupant behaviours inherently have a significant impact on net energy demand and the occupants' collective comfort (Guerra-Santin *et al.*, 2016; Liisberg *et al.*, 2016; Tagliabue *et al.*, 2016; Yousefi *et al.*, 2017). Their behaviours themselves are likewise bound to beliefs. s. Personality traits (Schweiker *et al.*, 2016), internal rendering colours (Wang *et al.*, 2018), perception of environmental control (Schweiker and Wagner, 2016; Yun, 2018) and even hearing other occupants describe comfort properties (Wang *et al.*, 2018) citing (Höppe, 2002) can affect occupants' beliefs about the ecosystem they reside.

Nondomestic buildings with poor thermal performance represent 66% of all building stock in the US and 75% in the (Lee *et al.*, 2019) which 60% are expected to still exist in 2050 (Pomponi *et al.*, 2015). Heating contributes 46% of UK energy demand with 86% of heating delivered by gas-fired systems (Chaudry *et al.*, 2015). Heating is an ecosystem-sensitive consumer in a sense changing the operational state of any discrete space within a building affects the heating of the remaining spaces. Given energy performance policy and plans to decarbonise the grid, heating perhaps deserves special attention despite compliance currently focusing on carbon emissions. Intuition suggests envelope thermal performance and heating, ventilation and air conditioning (HVAC) upgrades should be given precedence in the decision-making process, however; the former is not suitable for discrete spaces, and both are based upon the assumption that high heating demand is a system performance rather than system mismanagement problem.

Previous works identify sensitivity to occupant behaviours (Corgnati *et al.*, 2017), climate (Rastogi, 2016) and underutilisation (Gupta and Gregg, 2016). These highlight that retrofit decision-making is possibly better thought of as an exercise in risk aversion rather than identification of optimum. Rastogi offers a methodology for generating synthetic weather data for assessing retrofits and designs under probable climates. Lee *et al.* (2018) discuss a complementary Monte Carlo-based risk aversion method which mitigates some superstitions. Both are innovative approaches to decision-making but are susceptible to critical failures attributable to misguided assumptions. Gupta and Gregg (2016)identified a similar mismanagement hypothesis as discussed in this paper suggesting manual intervention from staff or some level of local smart radiator controls though they were not able to test the hypothesis. In a similar theme, this paper simulates lighting retrofits using explicitly known utilisation and two climates to demonstrate how heating management strategy for low utilisation spaces affects energy performance. The results are used to demonstrate that in the high heating demand is primarily a symptom of poor heating strategy management rather than envelope thermal performance or HVAC system efficiencies.

2. Methodology

Using a bespoke building model interfacing library, this paper demonstrates the necessity of using class registration data during retrofit analysis. This is achieved through a discussion of how lighting contributes to net energy demand when utilisation deviates from design occupancy. The results of 100 EnergyPlus and 19 Simplified Building Energy Model (SBEM) lighting and heating management retrofit simulations are used to explore the implications for decision-making, building operation, legislative compliance and energy scheduling and climate manipulations are exclusively incorporated to EnergyPlus simulations due to SBEM's limited flexibility. The tool used for scheduling both utilisation and building management systems (BMS) is described along with the cost methods used to for cost-benefit analyses.

2.1. Virtual case study

The seventh floor of the University of Strathclyde's Graham Hills Building was used for the study. The building was constructed between 1957 and 1959 which is two years prior to the introduction of the Building (Scotland) Act 1959 and six years prior to the Building Standards (Scotland) Regulations 1963. Therefore, the building's design was not bound to any meaningful performance regulations. However, it underwent staged building services retrofitting between 2000 and 2009 where HVAC, domestic hot water (DHW) and lighting were upgraded to be compliant with the Part L2B minimum standards at the time of installation. The floor is 2869m² with 13 teaching spaces of which 6 are utilised and1 is reserved with zero density presence.. The remainder of the space consists of43 offices and 23 secondary spaces. The floor below and partial floors above are retained for heat transfer calculations only. Opaque envelopes have a U-value of 1.7W/m²K and glazing a U-value of 5.68/W/m²K. Lighting efficacies are based on the National Calculation Method (NCM) lamp templates which best represent the fixtures as would be the case for any L2B survey. The floor is naturally ventilated with heating served by a low-temperature hot water boiler (LTHW) with a SCoP of 0.738 and delivered via a wet radiator. The two toilets have local extract fans with a specific fan power of 0.8W/l/s. There is no HMS present. The base model was created in DesigBuilder 5.4 and exported into SBEM 5.4.b and EnergyPlus 8.6.0. The disparity between lighting definitions in the models was resolved through standardised injection of efficacies and units from the NCM activity database including design illuminance levels.

2.2. Scheduling

Three standards and two complementary HMS-supported schedule scenarios were created for none-NCM spaces which represent the building's registered real world. Presence and density are taken from the class registration system.

NCM: A collection of standard schedules used for design and compliance modelling. These assume consistent presence across every standard weekday with separate near-zero utilisation schedules for weekends and holidays. In SBEM, these schedules are ignorant of both the real world and calendar whereas under normal circumstances outwith this paper, in EnergyPlus they are only ignorant of real-world utilisation. In this paper, NCM schedules are bound to a synthetic climate calendar akin to the theme of Rastogi (2016)'s synthetic weather in the sense that while climate data from 2016 and 2017, the 2016 calendar has been offset to match the 2017 day numbers.

Explicit/Implicit: Custom utilisation schedules are generated for all teaching spaces, which are record in the university's class registration system. Utilisation during occupied periods is defined separately for each registered period based on the registration system's definition of each space's capacity and the number of occupants registered for the class. Lighting is defined as Boolean-state based on the present state from the registration system. Where a teaching space has registered periods with zero occupant density the zone is considered in use with zero density. Finally, explicit scheduling considers that a teaching space with zero entries in the registration system has unknown utilisation and are assumed to be utilised as defined by the NCM. The Implicit scenario assumes that the registration system is complete and therefore any teaching space which has no entries in the system is never utilised during schedule year.

Explicit- / Implicit-BMS: Extending the Explicit and Implicit schedules, the rules applied to create the scenarios are used to define HMS system configuration. The data from the registration system used to generate each teaching space's utilisation and lighting schedules are used to modify the heating availability schedule of each space to prevent EnergyPlus from warming the spaces when no occupants are present. A preheat period is added to each presence period at one hour as per the default assumption.

2.3. Lighting design and BMS cost methods

Lighting and HMS installation cost methods were created through reference to a lecture from Philadelphia University and price estimates from the SPON's 2018 Mechanical and Electrical Services Price Book 2018.

2.3.1. Lighting (R-LIG)

Lighting retrofit costs are identified using photometrical computation (Lumens method) as documented in the Philadelphia University Electrical Installation lecture 11. The method uses photometric data to estimate the number of luminaires required to light a given environment through reference to luminaire efficacy, and utilisation and maintenance factors . Given as:

$$N = \left\lceil \frac{EA}{lm.UF.MF} \right\rceil \qquad k = \frac{LW}{(L+W)Hm} \qquad C = N(Fhl + Lc)$$

N: Number of luminaires, **E** = Target lux level for the zone. Where the target lux level is taken to be the design or "light_lux" value from the NCM activities database as per the binding discussed in 4.2.1, **lm** = Total luminous flux from each luminaire, **UF** = Utilisation factor identified from the luminaire's photometric data from the room index (**k**), **MF** = Maintenance factor **- k**: **L** = Room length, **W** = Room width, **Hm** = Ceiling height – work plane height **- C** = Total cost in £, **F** = Location labour cost adjustment factor, **N** = Number of luminaires, **h** = Installation luminaire/hour, **l** = Labour cost £/hour, **Lc** = £/luminaire.

2.3.2. Building management system (R-BMS)

Being a computerized system attached to local control measures, the HMS cost method is a function of the number of registered zones. The method was reduced to two primary costs, Head Equipment priced at £15,000 and Intelligent Unitary Controllers at £500/IUC. The cost method is given as:

$$C = Hc + NI$$

C = Total cost of installation in £, **Hc** = Global cost for head-end equipment (software, computer, commissioning) in £, **I** = Unit cost for each intelligent unitary controller £, **N** = Number of IUCs.

3. Results

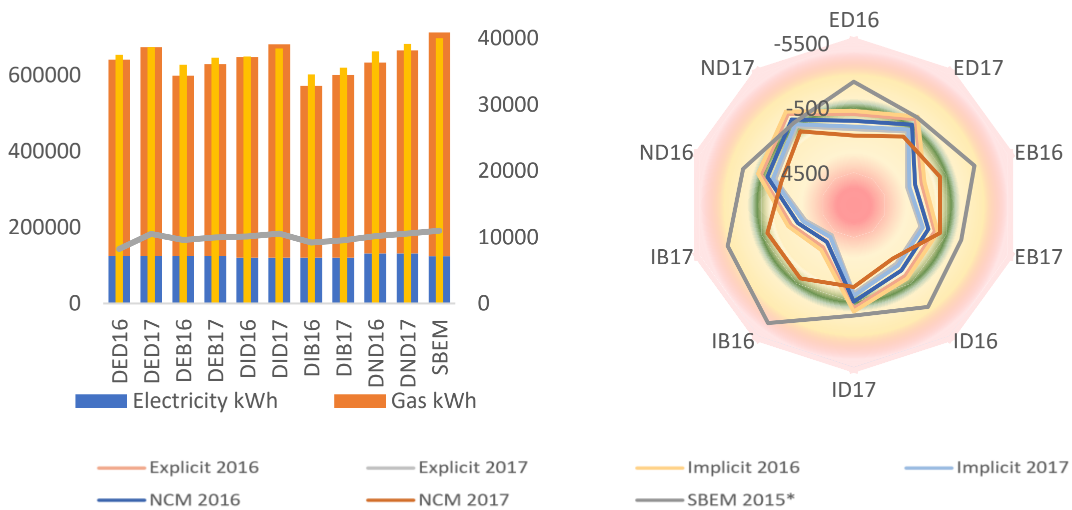


Figure 1 & 2: Estimated annual running cost (right y), consumption and emissions (left y) by Schedule-Climate / engine, and Schedule-Climate scenario running cost disparity. Labels represent strategy and year <schedule>-<BMS>-<year> where (D)efault, (E)xplicit, (I)mplicit, (N)CM, and (B)MS

Where NCM scheduling is considered as design the Explicit scenario results in a 52% reduction in presence hours for the teaching spaces and the Implicit scenario resulting in a reduction of 86%. Figures 1 and 2 show the base model annual net energy demand for each Schedule and Climate (Schedule-Climate) scenario and how they compare to one another. Notably, Explicit- / Implicit hold the highest and lowest annual consumption dependent on whether teaching space heating is managed.

3.1. Schedule presence

Figures 3 and 4 show the difference between NCM and registration system presence demonstrate the disparity cumulative presence and overlap between the NCM and registration system schedules for teaching space GH818. This space has the second-highest presence hours and the greatest overlap between NCM and registration system schedules. There is no cooling in this building however, it is worth noting utilisation during the cooling period is significantly lower than in NCM.

Table 1: Teaching space presence hours by Schedule

	807	813	816	817	818	863	898	801A*	801B*	801C*	801D*	801E*	801F*
NCM	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134
Explicit	---	745	639	611	633	483	675	2,134	2,134	2,134	2,134	2,134	2,134
Implicit	---	745	639	611	633	483	675	---	---	---	---	---	---
%Imp	0.00%	34.91%	29.92%	28.61%	29.66%	22.63%	31.61%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

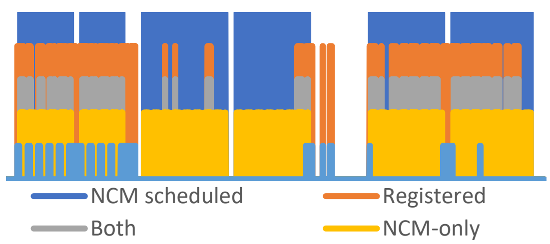


Figure 3: Schedule scenario overlap GH818.

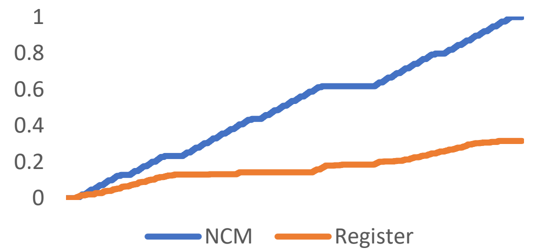


Figure 4: Cumulative presence GH818

3.2. Schedules, lighting and net building energy demand

Table 1 shows annual lighting energy consumption for teaching spaces for each Schedule scenario. NCM scheduled teaching spaces to contribute 20% of the total lighting demand equivalent to 10% of the buildings annual grid-supplied electricity demand. However, with registration system scenarios their contribution is reduced to 10% and 3.6% for Explicit and Implicit scenarios respectively. In absolute terms, these changes reduced grid-supplied electricity demand by 6.8MWh and 10.8MWh. Conversely, absence of internal gains from assumed presence increased natural gas demand for heating by 14.5MWh and 25.1MWh with 2016 climate data and 15.2MWh to 27.3MWh with 2017 climate data for Explicit and Implicit scenarios compared to their NCM counterpart. The increased heating demand is explained primarily by the absence of an HMS. Since an HMS is not present the teaching spaces are heated needlessly, and their heating demand is not mitigated through latent or lighting heat gains.

The relationship between lighting and simulated natural gas demand is not easily expressed due to the temporal, seasonal, utilisation (presence, density, humidity changes), external gains and the latent value internal gains from lighting and occupants. Even when adjacency awareness is ignored, a Wh of electricity consumed by lighting is rarely if ever equivalent to 1Wh of net energy demand due to heat produced by luminaires. Comparing the two registration system 2016 Schedule-Climate scenarios without an HMS against NCM-2016, annual heating demand for teaching spaces increases by 17.5MWh and 28.9MWh for Explicit and Implicit, respectively. The increased demand can be used to estimate the monetary value of each unit of electricity that would have been consumed by lighting in the teaching Heat gains from lighting contributed 23.8% and 23.3% of each teaching space Wh natural gas demand for Explicit and Implicit scenarios though this is reduced to 21.3% when only the academic year is considered. Factoring latent and lighting gains with the existing lighting system into the increase in net energy demand reduces the value of each kWh electricity saved from lighting consumption to 50% and 46% in net energy demand kWh for Explicit and Implicit, respectively. In contrast, Implicit-2016's kWh/kWh lighting to net energy ratio retains 3.1% above 1:1 when heating is managed. In summary, lighting consumption and net energy demand do not have a 1:1 relationship. Under design conditions this means each Wh lighting is worth 1Wh of electricity and a fraction of 1Wh of the heating demand, in the case of this building 1.84Wh. Therefore, under design utilisation each Wh of lighting reduces emissions 0.181gCO_2/Wh and £0.00003/Wh reducing its effective unit cost to £0.1253/kWh. Whereas, Implicit-2016's lighting consumption demand reduction of 10.6MWh electricity increases heating demand by 2.53MWh, nullifying 0.3tCO2 of the electricity-related emissions reduction and increasing the £/kWh cost of the new gas consumption from £0.0358/kWh to £0.044/kWh.

3.3. Lighting retrofit

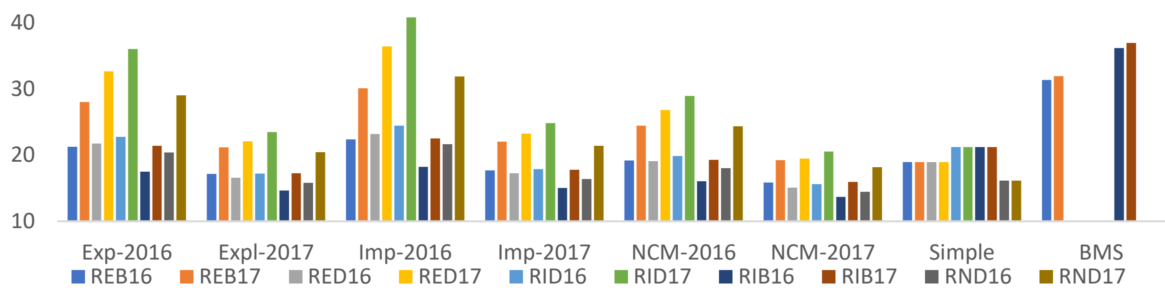


Figure 5: Schedule-Climate scenario relative discounted payback periods at 3.5%

Figure 5 shows the lighting retrofit for the virtual case study in terms of discounted payback period based on the difference between the base model simulated annual running of the x-axis and the savings from the bar labels' associated Schedule-Climate scenarios. BMS represents payback periods where both Schedule-Climate base model and cashflow values are based are consistent. Finally, simply represents payback where net energy demand is ignored As with discussion in 4.2, the discounted payback period is volatile depending on the chosen Schedule-Climate scenario for the base model, and the scenario assumed to produce the closest approximation of the annual run cost savings. Most SBEM results never return on the capital investment at a 3.5% discount rate. Across all scenarios where an HMS is not included in the base model estimated running cost, the payback period difference where x-axis and bar labels do not align ranges from 65% to 162%. SBEM, excluding one result at 55 years has a maximum range of 190%.The difference is between 46% and 88% at the bank base rate which is relevant to later compliance discussion. However, where HMS is presented the range is only 18%. A discount rate of 7% is often suggested for private projects. When this rate is considered, 38 Schedule-Climate scenarios fail to achieve a positive return on investment. The main lighting retrofits (R-LIG) for bars labels as "D" in the BMS label flag are calculated based on the lighting capital cost £83,112 whereas each with "B" for the flag includes £21,500 for the HMS. with a total cost of £104,612. Despite the extra 26% cost the payback period for all heating managed comparisons not compared to the heating managed base model estimate a payback period of lower than any other Schedule-Climate of without an HMS. A key feature of the BMS group is that using the Building Services Compliance Guide efficiency credits method of representing a BMS would not achieve a positive return on investment even though the cost used is ignorant of 66 zones which would normally need to be included in the price. Furthermore, the efficiency credits method would overestimate gas contribution to annual running cost by £3,000 to £3,300 for Implicit 2016- and 2017-HMS respectively.

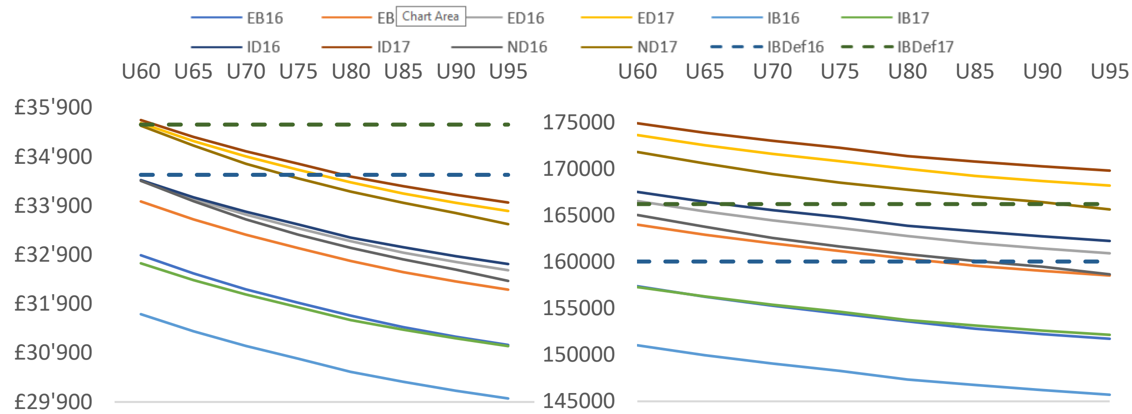


Figure 6: Annual running cost post-retrofit all lighting constant efficacy upgrades at the number of on the x-axis label in lm/cW. Series names represent Schedule-BMS-Year

Figure 7: Annual kgCO_2 post-retrofit for each retrofit with baseline 2016 / 2017 HMS.

Running costs improve in every retrofit scenario however, it can be seen in Figure 6 that the HMS state of each scenario supports previous discussion on net energy demand in low utilisation areas. When there is no HMS the savings from retrofitting are diminished proportionally to the corresponding NCM schedule of each Schedule-Climate. Furthermore, estimated running costs for design utilisation appear lower than with calibrated utilisation but no HMS. Compared to NCM savings as efficacy increases, lower utilisation results diverge from NCM savings further diminishing in return. In contrast, where an HMS is present running costs are significantly lower and become increasingly proportional to NCM scenarios as efficacy increases. However, carbon emissions better illustrate the underlying concern explored in this paper. Ignoring the inherent benefit of an HMS as noted elsewhere, retrofitting the lighting without HMS results under NCM utilisation would yield greater returns than with calibrated utilisation despite the 96.5% reduction in teaching space lighting demand for Implicit- scenarios. Horizontal dotted lines on figures 6 and 7 represent baseline running cost and carbon emissions for each Implicit Schedule-Climate with the HMS. Estimating from SPON's default LED luminaire and labour cost, to achieve those lines through lighting retrofit requires three times the cost of the HMS was it priced based on the method described in 2.3.2. However, a rudimentary installation as discussed by Gupta and Gregg (2016) could ostensibly be installed for less than £1,000 using smart radiator valve controllers.

4. Discussions

More often than not it is either not possible to meter a discrete space or there is no metering available which means there is rarely a meaningful opportunity to use operational data unless servicing is homogenous, and the discrete space represents a significant portion of the total gross internal area.

4.1. Heating management

It is clear from all dynamic simulations where Schedule-Climate scenarios are considered that low utilisation without an HMS has severe adverse effects on the virtual case study's net energy demand, namely its HVAC demand. Grid-supplied electricity demand was reduced by 8.3% and heating demand increased by 5.0%~ for both 2016 and 2017 Implicit Schedule-Climate scenarios without an HMS. However, the impact on the four meaningful metrics, net energy demand, carbon emissions, running cost and cost per kilogram carbon, was volatile depending on the base model Schedule-Climate scenario. Net energy demand increased and running cost decreased for all Schedule-Climate scenarios though not proportionally, carbon emissions and cost per unit carbon did not behave intuitively Were a simple estimation based on reduced lighting used to compare NCM to Implicit, a reduction in 1.97 $kgCO_2/m^2$ would be expected. However, the heating demand increase reduced this to 0.07kgCO2/m² for 2016 and caused 2017's to increase by 0.09 $kgCO_2/m^2$. The results are further compounded when $kgCO_2$/£ is considered, the suggested metric for equiproportionate abatement where a lower value shows greater potential for compliance-oriented application. NCM 2016 surprisingly suggests greater opportunity than NCM-2017, and Implicit-2017 less opportunity than Implicit-2016.

Introducing an HMS to Schedule-Climate scenarios resulted in significant improvements across all metrics, including up to 6$kgCO_2/m^2$ estimated annual emissions for Implicit compared to NCM. Additionally, the expected NCM > Explicit > Implicit relationship was realised. This was not exclusive to emissions The abatement metric now favoured Implicit, and NCM and Explicit were on par. This translated over to lighting as well where although the initial 1.84Wh net energy value of each Wh electricity consumed by lighting e was reduced to 0.5Wh and 0.46Wh without an HMS for Explicit and Implicit respectively, introducing an HMS improved the net energy unit value to 1.03Wh. The case study has no comfort cooling, and the absence during the summer as highlighted in Figure 3 would significantly reduce cooling load, however, GH818 at least is almost never occupied during the cooling period and therefore its cooling demand would be all but wasteful. Though, it is worth noting that all teaching spaces which are not GH801* have NCM scheduled adjacencies whose cooling demand would inherently be slightly reduced. The case study was made aware of the presence of adjacent floors to improve heat transfer calculations; however, the principle of scheduling lower utilisation will only further be skewed as other floors are calibrated.

Without an HMS the case study suffers from reduction in internal gains to the point where for some metrics the 70%~ reduction of presence hours for 23% of the building does not appear significant compared to design occupancy. Not only does low utilisation have a significant effect on simulation results, without management Schedule-Climate scenarios behave unpredictably and lighting waste heat's net energy unit value is roughly twice what it should be. Failure to manage dependent consumers results in volatility across performance metrics that suggest there is an envelope performance and/or HVAC efficiency problem. However, the results show that retrofitting these would remedy the symptoms rather than source of the problem, needles exertion of the HVAC system.

4.1.1. Heating management and compliance

BMS simulation for compliance is not well-defined due to the absence of persistent scheduling data.. The compromise for implementing HVAC control measures is to increase the CoP of heating systems by the relevant allowance identified from the Building Services Compliance Guide. In the case of the case study LTHW boiler, this could be an increase of 4%. The improvement from this is insignificant for Schedule-Climate scenarios without an HMS. Using the SBEM results, which is the most favourable scenario for the efficiency credits method, the improvement only improves heating demand by 7.68kWh/m² or £789/annum. The efficiency credits method is priced on the entire discrete space which would cost £46,000. Even using the MEES DPP rate of 0.75% the efficiency credits method would take 77 years to payback.

The modelling method used in this paper can be applied to the extent registration data is available and is not constrained by a full-building installation. The method, however, faces challenges for compliance modelling for L2B or MEES where it is not yet clear how scheduling would affect the standard energy rating (SER). The reference building is based on the geometry and scheduling of the actual model but HMS as defined in this papers not part of the reference definition. The implementation takes advantage of the heating availability scheduling, which inherently transfers to the reference building. This would mean that if the justification for accepting the approach were accepted by the governing body, accredited level 5 software would need updates to their Notional and Reference building model creation processes.

4.2. Lighting retrofit

The simple calculation bracket presented in section 3.3 serves two purposes 1) it shows how Schedule scenario affects the payback period with a 26% increase despite teaching spaces only representing 23% of gross internal area. 2) The results demonstrate why simple tools claimed to be suitable for nondomestic buildings such as those provided by Emerson, Spirit or Regency Lighting become increasingly inappropriate as utilisation decreases. The results from these tools are not necessarily wholly spurious if the building is notably better insulated and has high utilisation since as noted in 3.2,79% to 76% of gains lost through absence in Schedule scenarios were associated with latent gains from occupants.

Each of the standard six Schedule-Climate scenarios compared to results from all eleven, including SBEM are highly disparate with set comparisons deferring between 48% and 190%. This is obviously not reliable, excluding comparisons between NCM-2016 and NCM-2017 which is 20% to 41% at 3.5%. NCM scenarios highlight sensitivity to climate though at the bank base rate the payback period is only 2 year longer for 2016/2017 to 2017. However, when an HMS is introduced to Schedule-Climate scenarios the maximum difference is only 18% when compared to the retrofit's base model HMS counterpart at 3.5% and only 10% at the bank base rate. This may be attributed to the significantly reduced natural gas demand and retained greater than 1:1 lighting electricity's net energy value when teaching space are managed by the HMS. The HMS was expected to reduce utilisation related heating demand volatility however, the reduced volatility resulting from climate had not been considered before exploring the results. The difference in base model heating demand between Implicit and Implicit-HMS ranged from 81,200kWh and 109,800kWh for 2016 and 2017.These results show why dependent consumer management is not just relevant to mitigating counterintuitive behaviours resulting from retrofitting independent consumers.

Constant efficacy lighting retrofit simulations demonstrate that although improvements are realised across all metrics, the results indicate installation would result in better energy performance if the building was operating at design utilisation despite the significantly higher presence hours. That is, not only would the savings and subsequent cost-benefit analysis results be skewed by NCM over real utilisation schedules, implementing any of the eight full building lighting retrofits without an HMS would result in poorer performance than design utilisation, including running cost. It is universally more expensive to operate the building without an HMS than it is to operate at design utilisation post-retrofit. In terms of Part L2A, this may result in a pass that is underserved and MEES liability would become increasingly concerning.. Where heating is unmanaged, it may receive an undue exemption from upgrade requirements, and the decision-making process may lead to selection strategies which are ineffective to the real world. Current discussions in the private rented sector have turned towards the extent which compliance-led retrofits need to align before liability is a legal concern. ESOS is bound to operation net energy demand rather than emissions and therefore without an HMS the retrofitting lighting would have a negative effect on next stage of report which would not be apparent until 2023. Finally, with the electrification of the grid targets, ignoring heat management would have knock-on effects in terms of lifecycle emissions and reporting. All-in, retrofitting lighting in low utilisation areas without first implementing an HMS is inadvisable for the case study despite supporting results from other research on high utilisation buildings.

4.3. The implication for ESOS-, Part L2B- and Section 63-led retrofitting

Depending on whether NCM or Implicit Schedule-Climate scenarios are used will be the difference between teaching spaces contributing 20% to the overall lighting and 3.5%.Ignoring net energy demand, this equates to an assumption of business, as usual, having a net present value of £10,133 or £8,931 more than expected over 7 years at 3.5% and 7% respectively. This would also be the difference between lighting appearing as 41% to 61% of a Scottish EPC band rather than 7% to 12%, or 11% and 65% of an English EPC band – based on the current SER. ESOS prior to considering retrofitting, however, would perhaps be more concerning since, without some correlation between the reported operational and simulated fuel demands, calibration is untenable.

In terms of MEES for England, Wales and Northern Ireland, the difference in lighting energy consumption is nearly equivalent to paying for the lighting retrofit costs associated with the teaching zones alone less than 3 years outwith the 7-year retrofit measure exemption cut off. Using constant efficacy retrofit simulations, it was shown that unmanaged heating in low utilisation spaces not only resulted in higher running cost estimates than of design utilisation despite 86% lower presence hours in registered spaces. Additionally, retrofitting causes the building to perform worse than estimated for design utilisation. This is not necessarily an explicit concern for decisions made purely for MEES or Section 63 compliance since compliance is often considered less about reducing carbon emissions and more about ticking a box. However, it will not help the reputation of consultants. This should be of particular concern to consultants since conversations surrounding consultant league tables, and partial auditing of 100% of models have been discussed as necessary for MEES since 2013. ESOS and retrofit-as-service which are both bound to operational net energy demand currently are most at risk from failure to manage dependent consumers, and successful electrification of the grid is intricately linked to fuel management. In terms of policy and as service decision-making, lighting on its own is unadvisable by any metric.

None of the Schedule-Climate scenario comparisons are within the 7-year MEES exemption, and therefore the lighting retrofit would not need to be applied or considered as part of a strategy package. However, it does reduce carbon emissions by 13% to 17% for NCM and Implicit-BMS scenarios comparisons respectively when results are compared to their respective base model Schedule-Climate scenario. Although a boiler upgrade was omitted from this paper, it was estimated that were a boiler replacement retrofit included with the R-LIG + R-BMS package and priced using SPON's; the retrofit package payback period would decrease from 32 to 26 years for the lower bound estimate despite the £14,000 estimated boiler installation cost.

5. Conclusion

Design and low utilisation simulated energy performance across monetary, emissions and net energy metrics have a spurious relationship. While with some general understanding of the utilisation one may be able to use intuition to estimate how the relationship between independent on dependent consumers may affect net energy demand and possibly annual running costs to an extent, the relationship when considering Schedule-Climate and engine across all metrics is far from predictable. Though teaching spaces occupied less than 25% of the building, scheduling using registration data had profound effects on the simulation engines' analysis of the building. It is informally known that utilisation in other primary spaces is similarly low, though not registered meaningfully. Where all areas suitably registered, the negative impact would be significantly worse.

Low utilisation resulted in the building behaving erratically. Therefore, it appears necessary that accurate scheduling is a necessary first step not only in calibrating the energy model but also for comparing simulated and operational net energy demand. With an HMS in place, both Schedule-Climate scenario and retrofits measured across all metrics behaved intuitively. It, therefore, seems necessary to consider an HMS before any retrofit that may affect dependent consumers. Without management, retrofit options that appear to be most suitable for the building remedy the symptoms of low utilisation rather not the problems. Under normal circumstances, an HMS cannot be modelled in either EnergyPlus or SBEM and the standard efficiency credits method is not meant for low utilisation buildings. However, the method used in this paper accommodates realistic IUC behaviour modelling enabling meaningful HMS tuning with the utilisation-calibrated model. Finally, the HMS was three times cheaper than the SPON's estimate for the constant efficacy R-LIG to achieve at least the same running cost improvement as unmanaged heating 60lm/cW against 2017 climate and all unmanaged or design schedules emissions reduction until 85lm/cW against 2016. That is, until a global lighting retrofit has an efficacy of 30% greater than current BSCG requirements, spending at least three times the amount of the HMS cost would not result in better energy performance than solely installing an HMS.

Scheduling reduced lighting consumption in the associated spaces to the point where estimating the payback period exclusively on lighting energy consumption still resulted in payback periods longer than luminaire lifecycle even at the bank base rate. When considering net energy demand without an HMS the results were three and a half times greater than MEES exemption criteria at the bank base rate and well outwith the luminaire lifecycle for the at the public project discount rate. However, with heating management installed purely in the registered spaces with Implicit- scenarios were the worst case just over twice the exemption period. All teaching spaces bar one under Implicit- scenarios do not run long enough for LEDs to have merit. Therefore, T5s for teaching spaces may be a more suitable solution.

Rastogi (2016) demonstrates the necessity for a paradigm shift using static climate models during the design phase and retrofit decision-making. This paper expands on his observations through exploration of the impact of disparity between design and operational occupancy. Its main contribution to theory is proving operational heating demand inefficiency can be separated from system inefficiency and how the observations relate to policy. An alternative method of modelling BMS in EnergyPlus was created and shown to align building behaviours closer to what the behaviours represented at design occupancy which can also meaningfully represent real-world BMS installation in EnergyPlus. The industry currently relies heavily on faith in the consistency between virtual and real worlds, this paper both contributes to the literature that challenges these beliefs while providing a means of mitigating the concerns raised..

Acknowledgements

The research presented in this paper would not be possible without the considerable support from arbnco Ltd in both funding the corresponding author's MPhil and supporting their professional development over the last decade.

References

Chaudry, M., Abeysekera, M., Hosseini, S. H. R., Jenkins, N., & Wu, J. (2015). Uncertainties in decarbonising heat in the UK. *Energy Policy, 87*(Supplement C), 623-640. doi:https://doi.org/10.1016/j.enpol.2015.07.019

Corgnati, S. P., Cotana, F., D'Oca, S., Pisello, A. L., & Rosso, F. (2017). Chapter 8 - A Cost-Effective Human-Based Energy-Retrofitting Approach. In F. Pacheco-Torgal, C.-G. Granqvist, B. P. Jelle, G. P. Vanoli, N. Bianco, & J. Kurnitski (Eds.), *Cost-Effective Energy Efficient Building Retrofitting* (pp. 219-255): Woodhead Publishing.

Guerra-Santin, O., Romero Herrera, N., Cuerda, E., & Keyson, D. (2016). Mixed methods approach to determine occupants' behaviour – Analysis of two case studies. *Energy and Buildings, 130*, 546-566. doi:10.1016/j.enbuild.2016.08.084

Gupta, R., & Gregg, M. (2016). Empirical evaluation of the energy and environmental performance of a sustainably-designed but under-utilised institutional building in the UK. *Energy and Buildings, 128*, 68-80. doi:https://doi.org/10.1016/j.enbuild.2016.06.081

Hong, T., Sun, H., Chen, Y., Taylor-Lange, S. C., & Yan, D. (2016). An occupant behavior modeling tool for co-simulation. *Energy and Buildings, 117*, 272-281. doi:10.1016/j.enbuild.2015.10.033

Höppe, P. (2002). Different aspects of assessing indoor and outdoor thermal comfort. *Energy and Buildings, 34*(6), 661-665. doi:https://doi.org/10.1016/S0378-7788(02)00017-8

Janda, K. B. (2011). Buildings don't use energy: people do. *Architectural Science Review, 54*(1), 15-22. doi:10.3763/asre.2009.0050

Kneifel, J., Healy, W., Filliben, J., & Boyd, M. (2016). Energy performance sensitivity of a net-zero energy home to design and use specifications. *Journal of Building Performance Simulation, 9*(1), 70-83. doi:10.1080/19401493.2014.995708

Lee, J., McCuskey Shepley, M., & Choi, J. (2019). Exploring the effects of a building retrofit to improve energy performance and sustainability: A case study of Korean public buildings. *Journal of Building Engineering*, 100822. doi:https://doi.org/10.1016/j.jobe.2019.100822

Lee, P., Lam, P. T. I., & Lee, W. L. (2018). Performance risks of lighting retrofit in Energy Performance Contracting projects. *Energy for Sustainable Development, 45*, 219-229. doi:https://doi.org/10.1016/j.esd.2018.07.004

Liisberg, J., Møller, J. K., Bloem, H., Cipriano, J., Mor, G., & Madsen, H. (2016). Hidden Markov Models for indirect classification of occupant behaviour. *Sustainable Cities and Society, 27*, 83-98. doi:10.1016/j.scs.2016.07.001

Pomponi, F., Farr, E. R., Piroozfar, P., & Gates, J. R. (2015). Façade refurbishment of existing office buildings: Do conventional energy-saving interventions always work? *Journal of Building Engineering, 3*, 135-143.

Rastogi, P. (2016). *On the sensitivity of buildings to climatethe interaction of weather and building envelopes in determining future building energy consumption.* EPFL, Retrieved from http://infoscience.epfl.ch/record/220971/files/EPFL_TH6881.pdf

Ridley, I., Bere, J., Clarke, A., Schwartz, Y., & Farr, A. (2014). The side by side in use monitored performance of two passive and low carbon Welsh houses. *Energy and Buildings*, *82*(Supplement C), 13-26. doi:https://doi.org/10.1016/j.enbuild.2014.06.038

Schweiker, M., Hawighorst, M., & Wagner, A. (2016). The influence of personality traits on occupant behavioural patterns. *Energy and Buildings, 131*, 63-75. doi:https://doi.org/10.1016/j.enbuild.2016.09.019

Schweiker, M., & Wagner, A. (2016). The effect of occupancy on perceived control, neutral temperature, and behavioral patterns. *Energy and Buildings, 117*, 246-259. doi:10.1016/j.enbuild.2015.10.051

Space Management Group. (2008). UK Higher Education Space Management Project - Evaulation.

Tagliabue, L. C., Manfren, M., Ciribini, A. L. C., & De Angelis, E. (2016). Probabilistic behavioural modeling in building performance simulation—The Brescia eLUX lab. *Energy and Buildings, 128*, 119-131. doi:10.1016/j.enbuild.2016.06.083

Wang, H., Liu, G., Hu, S., & Liu, C. (2018). Experimental investigation about thermal effect of colour on thermal sensation and comfort. *Energy and Buildings, 173*, 710-718. doi:https://doi.org/10.1016/j.enbuild.2018.06.008

Yousefi, F., Gholipour, Y., & Yan, W. (2017). A study of the impact of occupant behaviors on energy performance of building envelopes using occupants' data. *Energy and Buildings, 148*, 182-198. doi:10.1016/j.enbuild.2017.04.085

Yun, G. Y. (2018). Influences of perceived control on thermal comfort and energy use in buildings. *Energy and Buildings, 158*(Supplement C), 822-830. doi:https://doi.org/10.1016/j.enbuild.2017.10.044

Specifying the information requirements for Forensic Delay Analysis

David Sanchez,[1] David Greenwood[1], Claudio Benghi[1], Vasil Atanasov[2] and Andrew Parry[2]

[1] Northumbria University, UK

[2]Project Advisors International

* email: david.greenwood@ northumbria.ac.uk

Abstract

Delays and late completion are familiar features of construction projects and are commonly accompanied by contractual claims and counter-claims as the parties concerned seek to protect their positions and mitigate their losses. In doing so, the organisations involved will often have recourse to consultants who specialise in the field of Forensic Delay Analysis (FDA). The FDA specialists then perform the analysis, and if required to, act as experts in presenting the results to dispute resolution or judicial hearings. The use of computer scheduling software, has for some time, been integral to the work of FD analysts. Despite this, typical FDA workflows have been heavily reliant upon imperfect, unstructured, manual information that requires a considerable time to collect and validate. This paper reports part of a project to develop a data-driven digital system for optimising the workflows and outputs a company already active in the field of FDA. It explores how FDA practitioners might exploit the growing availability of structured information within building information models to improve the efficiency and effectiveness of their work. The project comprised three stages: (I) to understand the workflows, technologies and operating context of the company; (II) to design a data-driven digital system for optimising workflows; and (III) to validate and refine that tool for market-testing. The results of Stages II and III will be made available in future publications. In Stage I of the study two main phases in the FDA process were identified, each with sub-phases. These begin with the FD analyst first establishing *when* and *where* a delay has occurred and quantifying its impact on completion. Next, the analyst must seek to determine *why* the delay occurred. This involves extensive audits of multiple information sources generated throughout the construction process. These sources typically exist in a variety of formats, included manually-generated material, and can be sparse, irregular, incomplete and sometimes contradictory. As a result, their extraction and validation take up a considerable part of the whole FDA process. The next stage involves the exercise of judgment as to which delay assessment methodology might be applicable to the information available and the current trends in judicial decisions. Finally, there is the production of a detailed report to the client and a presentation of the findings. The development of data-driven digital systems in FDA offers the prospect of enhanced visualization (hence, credibility) of these presentations. It also evokes the possibility of automating some of the time-consuming tasks associated with the process of claims preparation involving both quantitative and qualitative data that can be then subjected to numerical and non-numerical analysis. The requisite technologies are already available and could be integrated into a fully interoperable digitally-driven FDA system. However, the value of such a system would rely upon the collection and retrieval of adequate and credible information in a form that can be processed digitally: a situation that is currently rare. Following guidance such as that provided by the PAS documentation, there is an increased awareness amongst users of digital project models of their information requirements and how to specify them. A similar understanding and specification of the information requirements concerning the project delivery process would provide a basis for a data-driven progress monitoring system which could also, should the need arise, facilitate the extraction of evidence for the FDA process.

Keywords: Dispute resolution, forensic delay analysis, information requirements.

1. Introduction

Construction projects have been characterised as long-term, dynamic and complex (see, for example: Hillebrandt, 2000; Hughes, et al., 2006; Kärnä, et al, 2009) all of which, according Kraiem and Diekmann (1987) may contribute to their notorious tendency to suffer from delays. The problem of what McKinsey and Company (2017) call the poor 'schedule reliability' of construction projects appears historically ever-present and globally widespread (see, for example, Chan and Kumaraswamy, 1996; National Audit Office, 2001; CIOB, 2008; Gledson and Greenwood, 2017). Furthermore, 'completion on time', alongside 'completion under budget and according to specifications' is part of the so-called 'iron triangle' of project success criteria (Ogunlana, 2010). Over twenty years ago, Alkass *et al.* (1995: 335) declared that "delays are the most common and costly problem encountered on construction projects", while more contemporary authors (Zarei *et al.*, 2018) consider that delay analysis and management remain "critical tasks". This paper concerns the former (i.e. the analysis of delays) rather than the latter (their management). The immediate losses that result from project delays can be considerable and can have an impact upon all parties concerned: for example, the loss of beneficial use by the buyer (normally referred to in the UK as the Employer) and prolongation costs as well as opportunity costs, on the part of the project supply chain. Construction contracts apportion the risks of delay through mechanisms such as liquidated and ascertained damages, extensions of time, and other 'compensation' clauses. Explanations and analyses of these contractual mechanisms are available in the related literature; examples being the advisory protocols issued by professional bodies such as the UK Society of Construction Law (SCL, 2002; 2017) and the American Association of Cost Engineering (AACE, 2011) or in academic publications (for example, Kraiem and Diekmann, 1987; Wickwire, *et al*., 1991; Alkass, *et al.*, 1996; Scott, *et al.*, 2004; Arditi and Pattanakitchamroon, 2006; Braimah, 2013). However, contractual regimes cannot always cope effectively and amicably with the details, complexities and uncertainties of individual cases and there may be recourse to some form of dispute resolution (Clay and Dennys, 2018). A recent report (Arcadis, 2018) has estimated the global average value of construction disputes to be around US$43.4 million. With such sums at stake, the parties seek the services lawyers and consultants: one such service being Forensic Delay Analysis.

2. Forensic delay analysis

Forensic Delay Analysis (FDA) is a discipline that specialises in the analysis and presentation of delay claims. Typical FDA procedures are systematically described by such authors as Carmichael and Murray (2006), Braimah (2013) and Parry (2015): later in this article reference will be made to these and how they may change with the increasing digitalisation of the construction industry. The role of the FDA consultant is to produce convincing arguments that support or resist a claim on the grounds of *responsibility*, *causality*, and *quantum*. The allocation of responsibility may involve differences of opinion over how a particular event can be categorised in terms of contractual obligation. The first point of reference for establishing this will be the contractual agreement between the parties. The basic mechanisms provided by contracts have been mentioned above, as were their shortcomings in coping with the complexities and uncertainties of individual cases. Amongst these are the familiar complications over 'concurrent delays' (see, for example, Kraiem and Diekmann, 1987) and how to treat the 'float' or 'slack' that may be inherent within a contractor's estimated activity durations (see, for example, Householder and Rutland, 1990). Secondly, aside from the burden of responsibility, is the question of whether an alleged delay event has in fact impacted upon the completion of the project (i.e. the question of causality) and if so, how much impact it has had (i.e. the quantum). Establishing these matters will require access to various project records. In analysing these, there may be problems of: (i) selecting an appropriate delay analysis method to demonstrate both causality and impact; and (ii) the availability and accuracy of relevant project data; about the event, the project itself and the supposed impact of one upon the other.

The first of these differences is briefly discussed in the next section. However, it the second that is the main concern of this paper and considered in subsequent sections.

2.1 Delay analysis methods

There are several commonly-recognised delay analysis methods. It is outside the scope of this paper to discuss these methods in detail: this is done extensively in the aforementioned SCL Protocols (SCL, 2002; 2017) and AACE International Recommended Practice (AACE, 2011) as well as in academic literature (for example, by Braimah, 2013; Parry, 2015; and Keane and Caletka, 2015). Opinions as to what might be considered an 'appropriate delay analysis method' may differ with individual cases. The criteria may be subjective; for example, based upon familiarity with a particular method, or that the outcome of applying one particular method suits a party's interests more than the other's. External circumstances, such as the preferences expressed by the courts in Common Law jurisdictions, may sway the decision as to which approach is selected. More importantly, each delay analysis method requires specific information, such as reliable programmes (initial and updated) and as-built records, and their availability or non-availability may present a reason for choosing one method over another. The Society of Construction Law (SCL) first issued its Delay and Disruption Protocol in 2002, with a second edition in 2017. This was followed in 2011 by the AACE's International Recommended Practice on 'Forensic Schedule Analysis'. The authors of these documents are careful not to give a blanket endorsement of their recommendations nor do they propose that the documents should be incorporated as contractually binding agreements. Thus, the AACE Recommended Practice "is not intended to override contract provisions regarding schedule analysis methods or other mutual agreement by the parties to a contract regarding the same" (AACE, 2011: 11) whilst the SCL Protocol states that "is not intended that the Protocol should be a contract document" (SCL, 2017:1). In answer to the first of the two questions posed earlier (i.e. regarding the choice of an appropriate delay analysis method) the adoption of documents such as the SCL Protocol or the AACE Recommended Practice (pre-agreed or otherwise) for the management of delay in projects may reduce the likelihood of later arguments. There remains the second question; that of the availability and accuracy of the necessary relevant project data.

2.2 The availability and quality of relevant project data

Previous studies of the FDA process have revealed that it typically involves two phases: analysis and presentation. The analysis phase requires both quantitative and qualitative data. Carmichael and Murray (2006: 1008) refer to the "vast number of documents to be reviewed and people to be interviewed" and Alkass et al. (1995) estimated that this searching and organizing of information accounts for around 70 per cent of the effort in preparing a case. It appears that much of this effort is due to the inadequacy of available information. An observation by Major and Ranson (1980) was that incomplete and inadequate information represented "a common and substantial area of failure in site and head office management". This is a situation that was found to persist in more recent times, according to Carmichael and Murray (2006) and Craig and Sommerville (2007). Improved record collection and management systems have been proposed by Scott (1990) and by Carmichael and Murray (2006). This information is the essential data for comparisons to be made between how and when work what was planned and how and when it was ultimately carried out. Any of the aforementioned FDA methodologies could be rejected if its input data are flawed. In fact, it was the recognition of this that accounts for a major difference between the 2002 and 2017 editions of the SCL Protocol in determining a 'preferred method' as in the latter there is discussion of the advantages and disadvantages of analysis methods in relation to their data requirements and the quality and availability of those data.

2.3 The adoption of information technology for FDA

Parts of the FDA process are already heavily reliant upon computer software. The critical path method (CPM) and related techniques have some time ago become the norm for planning and scheduling construction activities (Wickwire *et al*., 1991). Presentations using CPM software have appeared in dispute resolution forums from the early 1970s and are now a widely accepted method for illustrating delay claims. Over the past twenty years there have been proposals for 'expert systems' that link ‘project management’ (i.e. scheduling) software to external databases for manipulating project data for the purposes of delay analysis and assessment (for an early example, see Alkass *et al*., 1995). However, there is still little, or no evidence of such systems being successfully adopted for the crucial tasks of information collection, retrieval and analysis., in fact, the FDA specialism is described by Gibbs *et al.* (2013: 49) as having “benefited the least from … developments in information technology”. The increasing adoption of Building Information Modelling (BIM) presents a further opportunity to enhance the FDA process by enabling the capture of relevant data and its later retrieval for analysis. Compared to that traditionally obtainable, the information within a digital model is potentially, according to Crotty (2011), not only more extensive, but of higher quality. It also creates the possibility of interfaces with other digital systems such as the real-time capture of field operations data for schedule monitoring (see, e.g. Taneja et al., 2011 and Zaher et al., 2018) thereby facilitating better record keeping practices and on-going contract administration. Furthermore, the combination of 3D models with a visualised and synchronised schedule, known colloquially as ‘4D’, has become a widely available technology for planning and construction (see, e.g. Gledson and Greenwood, 2017). This digital enhancement of construction scheduling presents great opportunities to improve, and even resolve, some of the issues surrounding the availability and quality of information for FDA. Thus, in the case of FDA the effective deployment of such digital technology could not only improve the visualisation, understanding and credibility of the arguments presented in support of a case, but could also potentially facilitate the retrieval of information required by FDA analysts at any point throughout the project. This last advantage is now examined further.

2.4 Information in BIM-based projects: problems revealed

Despite Crotty’s optimistic forecast of more extensive and higher quality interoperable information within a digital model, there remain inherent problems. The first concerns the availability of suitable data with which to populate the model. This may relate to uncertainty as to what information to specify, what to capture, or how to manage or structure it; or there may be a proprietorial reluctance to provide the information. The opposite scenario is one of information overload and chaos (see, for example, Gangatheepan, *et al.,* 2018: 260) as without its proper management the high volume of information possible could be counterproductive. Since 2011, when the use of BIM was mandated in the UK, publications such as PAS 1192-2:2013 (BSI, 2013) (‘internationalised’ and replaced by IS 19650) have advised on how to specify the information requirements for a digital model. In particular, the ‘Employers Information Requirements’ are defined as “the documented expectations of facility owners/commissioners for sharable structured information” (BSI, 2013: 51). Thus, with an increased understanding and uptake of these documents, owners and/or commissioners of built assets should be able to specify clearly the information needed at any time within a digital model. The question is whether any increased understanding of information requirements will assist the FDA process.

3. Methodology: an empirical study of FDA information needs

The study upon which this paper is based was a project to examine the prospect of exploiting digital technology to develop a data-driven digital system for improving the workflows of an organisation already active in FDA. This required a deep understanding of those workflows before attempting to design automated (or semi-automated) solution with more efficient functionalities that could be prototype-tested, validated and eventually commercialised. The project involved three research stages, namely:

Stage I: Situational Awareness: understanding the context of the company and its current workflows, its current technologies, as well as its outputs, services, and customers;

Stage II: Discovery and Decisions: the integration of digital tools and techniques and production of an initial capability model with performance criteria;

Stage III: Implementation and Validation of new technology-enhanced workflows leading to new business capability that can be market-tested and validated with appropriate refinements.

Different research and data collection methods were required for each of the stages. For Stage I (Situational Awareness) the research method was a combination of (a) desk study and (b) ethnography. The data collection method was, for (a) subject literature and IT product reviews, and for (b) by observation, unstructured interviews of FD analysts working within the host organisation, as well as access to archival material in order to develop an understanding of FDA workflows and outputs. Stage II required iterative technical development, including the identification (or in some cases, creation), testing, adaptation and modification of candidate software solutions and evaluation of their required functionalities. This required the creation of computer code, primarily to create interoperability between the various digital workflow solutions. Stage III, which concerned testing and refining the prototype, required focus-group evaluation and further development activities, respectively.

4. Findings: FDA information needs

The research problem addressed in this paper concerns the adequacy of available information for the envisaged data-driven digital system for supporting FDA. The prospects of obtaining such information, as already argued, may well be enhanced in a future digitalized project environment, but a prerequisite is the understanding of the information needs and how they can be met. In order to examine this further, an investigation was made of the current workflows within the host organisation, its use of software to support these, and its information flows and requirements. The section concludes with the potential for, and challenges to the introduction of a more automated data-driven system of FDA within the organisation.

4.1 Current FDA workflows

Based on the observations from Stage I of the project, Figure 1 shows a simplified FDA work-flow involving two phases. The first phase, *Analysis*, is to determine when and why delays happened and what were the effects. The second, *Presentation*, deals with how findings are to be demonstrated.

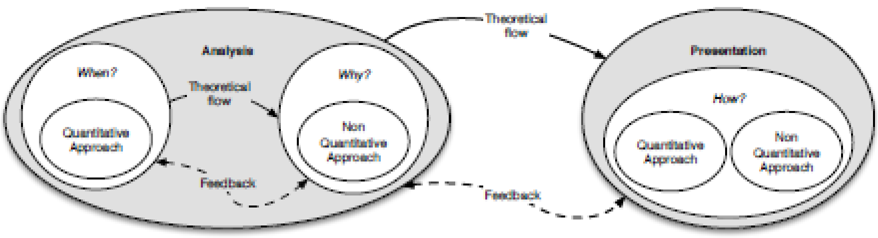


Figure 1: Forensic Delay Analysis simplified work-flow

The *Analysis Phase*, in turn comprises two interdependent and often simultaneous process: *Extraction* and *Examination* (*sc.* of information).

The *Extraction* process deals with ordering, tabulation and systematically cataloguing data that has been made available. During this process various validations are performed on the data, which may require significant clarification, rectification, or reconstruction.

The *Examination* process involves the analysis of extracted (validated) data, some of which can be accomplished using a quantitative approach (e.g. the numerical analysis of base-line *versus* actual schedules). The output of this phase is usually a detailed report (comprising narrative, graphs and numbers) and presentation slides. The situation is much as that described by earlier studies (e.g. Alkass *et al.*, 1995; Carmichael and Murray, 2006) save for the now-extensive use of computer software throughout the process. This includes common office software (Microsoft Office, Libre Office, iWork, Google Docs, etc.), computer spreadsheets (Excel, Calc, Numbers, Google Sheets etc.). However, these software applications are invariably used to gather data rather than to perform meaningful analysis. For example, spreadsheets are used to store and retrieve data (including graphical export mode) rather than for calculation or statistical purposes; extensive human intervention is still required for purposes of inspection, comparison and pattern recognition.

The *Presentation Phase* is supported by the use of presentation software (PowerPoint, Impress, Pages, Google Slides, etc.) and the Project Management software programs that have the strongest user base in the construction industry (i.e. Oracle Primavera P6, Asta Powerproject and Microsoft Project) thus allowing for the FD analyst to work in the same schedule presentation format as the data received.

4.2 Information flows and requirements

The flow diagram shown in Figure 2 is an overview on how data are exchanged between an FD analyst, the client (i.e. that has commissioned the FDA) and ultimately, the tribunal (or equivalent third-party adjudicator). The current extraction process relies heavily on the dissection of (mostly) unstructured electronic data and paper-based files, augmented by oral explanations obtained from interviewing key participants. The data involved in the *extraction* process can be both qualitative and quantitative, and although the *examination* process may at first appear to rely upon predominantly numerical data (e.g. to enable the comparison of base-line *versus* actual schedules) in reality the questions of *why* a delay happened and *what* were its effects are primarily answered by a more non-quantitative approach in which analysts try to create a logical network of causes and effect usually by performing examination, observation and deduction.

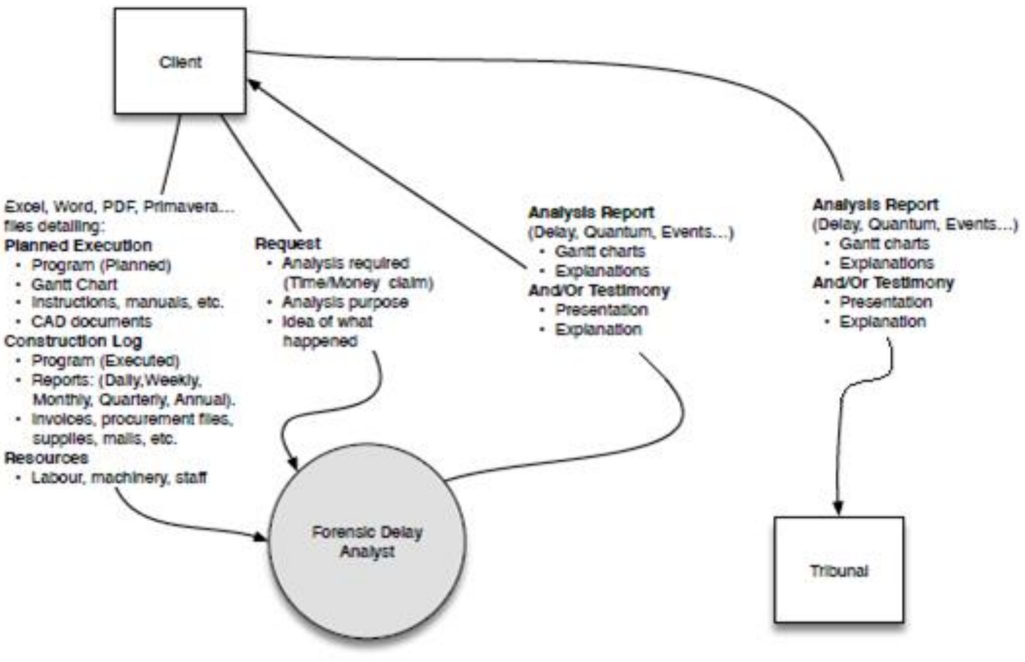


Figure 2: the flow of information in the FDA process

The *Examination* process then involves the analysis of extracted (validated) data, which, as already noted can be both quantitative and qualitative in nature. The output of this phase is usually a detailed report (comprising narrative, graphs and numbers) and presentation slides. There was an apparent anomaly in the non- use of available special software products that are targeted towards FDA. These include products that can automatically investigate variances between two or more schedules, (including those on different native platforms) such as Acumen Fuse, Change Inspector, Steelray Project Analyzer, and Schedule Analyzer. The creator of one of the aforementioned products claims that a variance analysis of schedules that would conventionally take 2-4 hours can be completed in under one minute (Deltek, 2017). However, the reluctance to use such specialist applications is likely to be because their utility is reduced or nullified if, as noted earlier, appropriate data are unavailable, or they are incomplete, unstructured, and unreadable. The opportunities to use analysis software is not limited to purely quantitative data. Stage I investigations revealed that much of the current information gathering for FDA was essentially qualitative, with data comprising unstructured, manually-generated information requiring a considerable amount of time to collect and validate. However, if such information could be digitally captured, ideally at source, then it can be more efficiently extracted. It should be noted that other disciplines, including social sciences (Fielding and Raymond, 1998), crime-scene investigation (Levy, 2015) or marketing (Rettie *et al.*, 2008) have information extraction procedures that are in essence similar to those performed by FDA and have developed Computer Assisted Qualitative Data Analysis Software (CAQDAS) to analyse large quantities of data contained in speeches, police declarations, interviews, and surveys. It is evident from Figure 2 (above) that the typical information interchanges in FDA could be readily accommodated by a BIM Common Data Environment (CDE). Field progress data could be added to the project model, including qualitative data that were digitally captured by use of a CAQDAS system. The capture of the relevant information within a project model could thus represent a dramatic improvement on the efficiency of the FDA *extraction* process. And finally, the digital nature of extracted information would permit the use of specialist software which could be integrated into a system for analysing both quantitative and qualitative data during the FDA *examination* process.

5. Conclusions

The increased availability of structured, machine-readable project data prompted by the growing adoption of BIM could have a constructive effect on the resolution of construction claims and disputes. Uncertainty about design and construction information is a frequent component in claims causation: this could be significantly reduced when supply chain organisations have access to the digital project model. One of the main problems for the FD analyst, indeed for all parties involved in claims and dispute resolution, is the availability and authenticity of records. Digitalisation of the contract administration process could enable automated or semi-automated digital record-keeping which in turn would provide structured, verifiable data upon which to base the resolution of claims and disputes. In terms of data analysis, a hybrid approach could accommodate both quantitative and qualitative data extraction and examination. These findings suggest that, subject to the availability of the requisite data in structured, digital form, it is indeed feasible for FDA workflows to be more efficiently and effectively performed. There is, however, a major challenge. The prospect of a data-driven digital process depends upon a quality and rigour of record-keeping which, by current evidence, cannot be relied upon. A possible solution lies in the PAS-1192 documentation described earlier and thanks to which, owners, designers and constructors are becoming more familiar with what information may be required in their digital project models in order to best exploit the capabilities of BIM. Thus, a set of 'progress information requirements', agreed at the contract stage could stipulate what data was to be captured, when, by whom, and in what format. It may be imagined that optimism bias (i.e. the fact that, despite evidence to the contrary, project participants would not admit to the likelihood of a dispute at the outset) would deter the use of such an agreement. However, there are other, more immediate benefits. Ready access to verifiable data should enable claims to be minimized; or when they arose, to be settled commercially (and even settled automatically using distributed ledger technology) rather than progressing to formal third-party proceedings, such as arbitration. Where disputes did occur, the availability to the FD analyst of structured digital data would greatly reduce the time and resource required for its analysis, and the presentation of the complex issues that are involved in a claim could be facilitated by the appropriate and agreed management and analysis of the digital records. The digitalisation of the dispute resolution process with appropriate feedback supported by artificial intelligence and machine learning would perhaps ultimately change the role of the FD analyst, from that of a contentious retrospective claims consultant, to pre-contract delay risk analyst.

Acknowledgements

The authors acknowledge the support of InnovateUK for their funding of the Knowledge Transfer Partnership, ID No. 1024572 under which the research related to this paper is being carried out.

References

Alkass, S., Mazerolle, M., Tribaldos, E. & Harris, F. (1995). Computer aided construction delay analysis and claims preparation. Construction Management and Economics, 13: 335–52.

Alkass, S., Mazerolle, M., & Harris, F. (1996). Construction delay analysis techniques. Construction Management & Economics. 14(5), 375-394.

AACE (American Association of Cost Engineering) (2011). International Recommended Practice no. 29r-03, 'Forensic Schedule Analysis'. April 2011. [Online]. Available at: https://web.aacei.org/docs/default-source/toc/toc_29r-03.pdf?sfvrsn=4 .[Accessed 26-04-2109].

Arcadis Contract Solutions (2018) Global Construction Disputes Report. Available at: file:///D:/00%20PUBLICATIONS%20IN%20PREPARATION/CIB%20World%20HK/Arcadis%20Global%20Construction%20Disputes%202018.pdf . [Accessed 04-02-2019]

Arditi, D., & Pattanakitchamroon, T. (2006). Selecting a delay analysis method in resolving construction claims. International Journal of project management, 24(2), 145-155.

Braimah, N. (2013). Understanding construction delay analysis and the role of preconstruction programming. Journal of Management in Engineering, 30(5), 04014023.

Broome, J.C. & Hayes, R.W. (1997). A comparison of the clarity of traditional construction contracts and of the New Engineering Contract. International Journal of Project Management Vol. 15, No. 4, pp. 255-261.

BSI (2013) PAS 1192-2:2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling. British Standards Institute, London.

Carmichael, S., & Murray, M. (2006). Record keeping for contemporaneous delay analysis: A model for effective event management. Construction Management and Economics, 24(10), 1007-1018.

Chan, D. W., & Kumaraswamy, M. M. (1996). An evaluation of construction time performance in the building industry. Building and Environment, 31(6), 569-578.

CIOB (2008) Managing the Risk of Delayed Completion in the 21st Century, Chartered Institute of Building, Ascot, UK.

Clay, R., & Dennys, N. (2018) Hudson's Building and Engineering Contracts (13th ed.). London: Sweet & Maxwell (U.K.).

Craig, N. & Sommerville, J. (2007) Records management and information processing on construction sites using digital, pen and paper. Records Management Journal, vol. 17, no. 3, pp. 201–215.

Crotty, R. (2011) The Impact of Building Information Modelling: Transforming Construction. New York, Routledge.

Deltek (2017) Deltek Acumen Fuse product sheet. Online PDF. Available at: https://www.deltek.com/en/products/project-and-portfolio-management/acumen/modules/acumen-fuse 5 [Accessed 07-05-2019].

Fielding, N. & Raymond, L. (1998) Computer Analysis and Qualitative Research. Sage Publications,

Gangatheepan, S., Thurairajah, N., & Lees, M. (2018). From information transmission to engagement in practice: A study on BIM enabled construction projects. In: ARCOM 2018: 34th Annual Conference - A Productive Relationship: Balancing Fragmentation and Integration, 3rd - 5th September 2018, Belfast, UK.

Gledson, B.J., and Greenwood, D.J. (2017) The adoption of 4D BIM in the UK construction industry: an innovation diffusion approach. Engineering, Construction and Architectural Management, 24 (6), 950-967.

Gibbs, D.J., Emmitt, S., Ruikar, K., and Lord, W. (2013). An investigation into whether building information modelling (BIM) can assist with construction delay claims. International Journal of 3-D Information Modeling (IJ3DIM), 2(1), 45-52.

Hillebrandt, P. M. (2000). Economic theory and the construction industry. London: Macmillan.

Householder, J. L., & Rutland, H. E. (1990). Who owns float? Journal of Construction Engineering and Management, 116(1), 130-133.

Hughes, W., Hillebrandt, P. M., Greenwood, D., & Kwawu, W. (2006). Procurement in the construction industry: the impact and cost of alternative market and supply processes. Routledge.

Keane, P.J. and Caletka, A.F. (2015) Delay analysis in construction contracts. John Wiley & Sons.

Kärnä, S., Sorvala, V. M., & Junnonen, J. M. (2009). Classifying and clustering construction projects by customer satisfaction. Facilities, 27(9/10), 387-398.

Kraiem, Z.M., & Diekmann, J.E. (1987) Concurrent delays in construction projects. Journal of Construction Engineering and Management 113 (4): 591-602.

Levy, B. (2015) The need for informatics to support forensic pathology and death investigation. Journal of Pathology Informatics, 6.

McKinsey & Company (2017) reinventing Construction: a route to higher productivity. Available at: https://www.mckinsey.com/~/media/mckinsey/industries/capital%20projects%20and%20infrastructure/our%20insights/reinventing%20construction%20through%20a%20productivity%20revolution/mgi-reinventing-construction-executive-summary.ashx.[Accessed 03-02-2019]

NAO (National Audit Office) (2001) Modernising Construction. Available at: https://www.nao.org.uk/wp-content/uploads/2001/01/000187.pdf. [Accessed 03-02-2019].

NBS (National Building Specification) (2016) 'What is Building Information Modelling?' Available at: www.thenbs.com/knowledge/what-is-building-information-modelling-bim.[Accessed 07-02-2019].

Ogunlana, S. O. (2010). Beyond the 'iron triangle': Stakeholder perception of key performance indicators (KPIs) for large-scale public sector development projects. International journal of project management, 28(3), 228-236.

Parry, A. (2015) The improvement of delay analysis in the UK construction industry. Unpublished PhD thesis. Available at: http://nrl.northumbria.ac.uk/27294/ 2. [Accessed: 06-02-2019].

Rettie, R., Robinson, H., Radke, A. and Ye, X. (2008). Caqdas: a supplementary tool for qualitative market research. Qualitative Market Research: An International Journal, 11 (1): 76–88.

SCL (Society of Construction Law) (2002) Delay and Disruption Protocol, 1st Edition. Society of Construction Law. Hinckley, Leicestershire, UK.

SCL (Society of Construction Law) (2017) Delay and Disruption Protocol, 2nd Edition. Society of Construction Law. Hinckley, Leicestershire, UK.

Scott, S; Harris, R; and Greenwood, D.J. (2004). Assessing the New United Kingdom Protocol for Dealing with Delay and Disruption. American Society of Civil Engineers, Journal of Professional Issues in Engineering Education and Practice, 130 (1) 50-59.

Taneja, S., Akinci, B., Garrett, J.H., P.E., Soibelman, L., Ergen, E., Pradhan, A., Tang, P., Berges, M., Atasoy, G., Liu, X., Shahandashti, M.S., & Anil, E.B. (2011). Sensing and Field Data Capture for Construction and Facility Operations. ASCE Journal of Construction Engineering and Management, 870–881.

Wickwire, J. M., Driscoll, T. J., Hurlbut, S. B., & Groff, M. J. (1991). Construction scheduling: Preparation, liability, and claims (p. 158). Wiley Law Publications.

Zaher, M., Greenwood, D.J., & Marzouk, M. (2018). Mobile augmented reality applications for construction projects. Construction Innovation, 18(2), 152-166.

Zarei, B., Sharifi, H., & Chaghouee, Y. (2018). Delay causes analysis in complex construction projects: a Semantic Network Analysis approach. Production Planning & Control, 29 (1), 29-40.

Information Exchange in Platform Approaches to Design for Manufacture and Assembly

Alexander S.J. Zhou*, Long Chen and Jennifer Whyte
Centre for Systems Engineering and Innovation, Department of Civil and Environmental Engineering, Imperial College London
* email: asjzhou@imperial.ac.uk

Abstract

Platform approaches to Design for Manufacture and Assembly (DfMA) advocate the mass-customization, repeatability and modularity from the downstream supply-chain to design process. It extensively relies on the design process to leverage the supply-chain to achieve best value of the project. However, current design decision making is often made inside the black box on account of a lack of effective information exchange originating from production systems. This research aims to enhance the information exchange from production systems to design as well as the interoperability and connectivity between design and production processes by linking Industry Foundation Classes (IFC) based Building Information Modeling (BIM) to data models for production. A literature review is conducted on current DfMA practices with a focus on industrialized building to formulate a synthesis in the framework of platform-based approaches. Propositions are made to identify the gap between conventional and platform-based DfMA approaches. In doing so, future research can be sought to formulate a robust and open approach for platform-based DfMA in industrialized building.

Keywords: Design for manufacturing and assembly, Building information modeling, Information exchange, Platform

1. Background and Introduction

There is an increased interest in Design for Manufacture and Assembly (DfMA) for the industrialized construction worldwide. In Singapore, DfMA is among the three key areas of construction industry transformation map (BCA, 2017: p.2-3). In Hong Kong, DfMA plays a vital role in implementing the offsite construction, particularly the modular integrated construction and weighs substantially in the performance metrics of innovation (DEVB, 2018: p.28 and 48). In the UK, from the *RIBA plan of work Designing for Manufacture and Assembly overlay* (RIBA, 2016) and recent response to Infrastructure Project Authority (IPA)'s call for evidence in new approaches for building (IPA, 2018), the UK's construction industry is transforming by maximizing the benefits from digitization, manufacturing and life-cycle performance including cost, sustainability and user experience (CLC, 2018). DfMA has become seen as a major process that underpins the industry transformation.

DfMA originates from embodiment design which is known as Design for X (Huang, 1996). Design for X has been developed as an "umbrella" for a range of specific purposes including manufacturability, inspectability, recyclability. It is composed of two parts, namely "lifecycle business process (x)" and "performance measures (bility)" (Huang, 1996: p.3). Pioneers studying Design for Manufacture (DfM) and Design for Assembly (DfA) have realized the great importance of design in product lifecycle performance. Especially cost effectiveness resulted from design is far more substantial than other processes (e.g. manufacture and assembly) (Bralla, 1996: p.14). An integrated approach combined platforms and DfMA for product management can contribute to the commonality and variety of product design by adopting repetitive, standard, modular details (Emmatty & Sarmah, 2012: p.699). Other benefits from the platform-based design have been also unveiled in many other industries in product development and production including cost effectiveness, time saving, reduced complexity, better capability in product updating and plant utilization (Simpson, 2004: p.4).

Platform-based DfX can incorporate various support systems including computer aided design and manufacture, computer aided process planning, and computer aided production management for efficient data exchange and decision making process during product development (Huang, 1996: p.4). More generic platforms can facilitate the systems integration not only in design and production, but also the back-end stages like the supply-chain management, reconfiguration, etc (Pirmoradi et al., 2014). Thus platform-based DfMA can be seen as a vehicle for information exchange across project delivery stages and systems. To ensure timely and precise information exchange becomes critical for design development. Several attempts in other industries have shown the great potential benefits in standardizing information exchange through configurable product design and platforms. In addition, the flexible manufacturing systems cannot succeed without the efforts from information systems and platforms for reconfiguration and information integration and collaboration in different stages of "product family extended platform" (Simpson et al., 2014: p.781).

In digitally-enabled industrialized building, Building Information Modeling (BIM) is often used for data and information exchange across domains and stages in project delivery. Industry Foundation Class (IFC) is the neutral BIM data exchange format and Information Delivery Manual (IDM) can store the required specification for information exchange in business process at particular timing (ISO, 2016). It has been regarded as a main approach to stream the design process by linking with different domain expertise. However, current challenges in the practice have threatened the information management without defining the base and exchange process (Lee et al., 2016). Inconsistency in the data structure and hierarchy as well as discontinuity in the data transfer between IDM and Model View Definition (MVD) also create barriers for information exchange. BIM data validation against the requirements of the MVD and the limitations of this data evaluation process have not been thoroughly studied, which results in syntactic problems, semantic errors, and unintended geometrical transformation (Lee et al., 2019).

The aim of this work is to review the current platform-based DfMA practices with a focus on information exchange based on literature in industrialized building. Different types of platform based DfMA are identified and classified firstly. Through literature review and synthesis (Webster & Watson, 2002), this research firstly summarized and classified the IDM-based information exchange patterns for industrialized building according to production strategies. The literatures were chosen with a particular focus on information exchange in platform-based DfMA for industrialized building. It then proposed to use the platform-based DfMA for more efficient information exchange. Finally, through cross analysis of literature, the limitations of conventional DfMA have been identified and discussed, while the corresponding solutions from platform-based DfMA have been proposed to address such problems.

This research acts a preliminary study for applying platform-based DfMA to information exchange in industrialized building, providing a new way for enhancing interoperability and connectivity between design and production systems (i.e. manufacturing and assembly) processes. The first research phase concerns theory development and is based on a literature review and conceptual modelling (logical reasoning). At first a thorough literature review was conducted in order to find the most relevant schemes and frameworks for information exchange of platform based DfMA for industrialized building. The second phase of the research concerns propositions of information exchange of platform based DfMA with a comparison from conventional DfMA practices.

2. Information Exchange for Platform-based DfMA

This part will mainly focus on current literatures on the DfMA and information exchange in industrialized building, as well as the platform-based DfMA framework in industrialized building.

2.1 DfMA and Information Exchange

The benefits of industrialized building come from the emergence of BIM in different perspectives including productivity, safety, quality, cost and efficiency (Eastman et al., 2009; Nawari, 2012). Existing research (e.g. information management for industrialized building) has shown their limitations in monolithic production strategy and lack of interlinkage with capability of production systems in the preliminary design stage. Key literatures are identified and summarized in Table 1 with regards to their different production and supply-chain strategies, key stakeholders and leading parties, and information management methods.

Standardization of information exchange between design, production, logistics and assembly processes in industrialized building has been a long-lasting topic. Information Delivery Manual for Precast Concrete (2009) is the first IDM standard for industrialized building based on the first version of US National BIM standard (NIBS, 2007). Then Eastman et al. (2010) further illustrated the rationales and a “use case” approach behind development of this national IDM standard. It is based three types of delivery methods in terms of different leading parties including engineer/architect, precaster and combination of the former both in the pre-construction stage. Nawari (2012) proposed a high-level IDM for offsite construction. The adopted production strategy follows Engineer-to-Order (ETO) process in which architect/engineer leads the decision-making process directly to the client before manufacturability studies carried out. An extended process to product modeling (xPPM) based on previous Georgia Tech Process to Product Modeling (GT-PPM) (Sacks et al., 2004) was developed aiming to improve the repeatability of information from both product model and architecture, and the IDM-MVD dataset (Lee et al., 2013). Berard and Karlshøj (2012) used an action research method to reengineer the information exchange process through engaging actors in the design and tendering with a focus on integrating product information. They argued that the success of IDM substantially depends on succinct terminology, modeling language and generic and flexible modeling process. A concept of product architecture model (PAM) is another key framework to facilitate in the DfMA information exchange in multistory industrialized building (Ramaji & Memari, 2015). Such a framework enables information exchange in both product-oriented and process-oriented approaches (i.e. the information exchange through the process maps, exchange models and task unit specifications) (Ramaji et al., 2017). The manufacturer and construction manager can be involved in a secondary way where the main decision is made in the architect and engineering domain. Despite the progressive development of IDM-MVD methods in industrialized building, current IDM-MVD practice has encountered barriers. These challenges include the complexity in producing process maps using Business Process Modeling Notation (BPMN), the poor traceability and reusability in exchange requirements and functional processes, the complexity in linking different information exchange files (Lee et al., 2013).

Table 1: IDM-based Information Exchange Patterns for DfMA in Industrialized Building

Production /Supply-chain Strategies	Authors	Industrialized building Method	Key Stakeholders and Leading Party (if any)	Information Management Method
ETO	Eastman et al. (2009) Berard and Karlshøj (2012)	Precast concrete components	• Architectural precaster • Or precaster-led • Or precaster as subcontractor	IDM-MVD
	Berard and Karlshøj (2012)	Prefabricated components	• BIM consultant • Product manufacturer • Contractor	IDM
	Ramaji and Memari (2015, 2018); Ramaji et al. (2017)	Volumetric modules (Composite steel and concrete volumetric modules, and others)	• Architect-led • Engineer • Manufacturer • Construction manager	IDM with extended MVD focus on integration and enrichment of building story and elements
	Yuan et al. (2018)	Prefabricated concrete components	• Architects led • Engineer • Assembly technician	DFMA-oriented parametric design
CTO (Configure-To-Order)	Malmgren et al. (2011) Jensen et al. (2012)	Configurable building system platform with prefabricated timber components	• Customers • Engineers • Product manufacturers • Assembly team	Product view method composed of the customer, engineering, production and site assembly views

ATO (Assembly-To-Order)	Nawari (2012)	Prefabricated components (concrete, steel, timber and others)	• Architect • Engineer • Manufacturer • Erector • Contractor	IDM
MTS (Made-To-Stock)	Berard and Karlshøj (2012)	Prefabricated components	• BIM consultant • Product manufacturer • Contractor	IDM

In order to address the obstacles, a configurable building system platform becomes an alternative solution to meet customization. It relies on early engagement of stakeholders' capacity to design stage. It also creates more flexibility in design while maintaining a high level of customization in fulfilling user needs. In a similar approach as MVD, multiple product views can visualize and facilitate the information exchange between stakeholders in different domains including customers, engineering, production and assembly (Jensen et al., 2012). Such CTO-based industrialized building has shown great capability in empowering customers value through standardized interfaces and products.

2.2 Platform-based DfMA in Industrialized Building

Mass customization is the main objective in fulfilling the most customer needs through a substantial number of products (Pine, 1993: p. 196). A platform-based product development is one of the tactics to drive mass customization (Simpson, 2004). Product platform often describes the product design practice using families with both competency in technological field and versatility in different customizing needs (Dodgson et al., 2008, p. 217). Current literature on technical platforms in industrialized building mainly focus on the product platform. Among different typologies of platform-based product design in industrialized construction research, the Jiao's typology remains a key reference in platform development which has been extensively used in earlier studies (Jansson et al., 2014; Jensen et al., 2013; Jensen et al., 2015a; Ramaji & Memari, 2016; Wörösch et al., 2015). Thus, this part adopts this method to summarize key literature covered in industrialized building in Table 2.

Table 2: List of Literature on Different Typologies of the Platform-based DfMA in Industrialized Building

Front-end Issues	Product architecture, product family and platform configuration, and product portfolio positioning
	➢ Product information in different production strategies (Winch, 2003) ➢ Configurable "products in product" method (Jensen et al., 2014) ➢ Product architecture model (PAM) (Ramaji & Memari, 2015)
Design and development issues	Balance standardization and versatility of building products
	➢ Housing product platform structure including product architecture, interface and standards (Veenstra et al., 2006) ➢ Technical and process platforms to standardize building product development (Lessing, 2006: p.187) ➢ Parametric models for configuration management of industrialized building systems (Jensen et al., 2012) ➢ Modular architectural view method to link the customer requirements to platform development (Wikberg et al., 2014) ➢ Exterior panelized walls platform optimization (Said et al., 2017)
	Design optimization:
	➢ A methodology for the optimal modularization of building design (Isaac et al., 2016) ➢ Exterior panelized walls platform optimization (Said et al., 2017) ➢ Tolerance: (Rausch et al., 2017) (Shahtaheri et al., 2017) ➢ Geometric variety control: (Rausch et al., 2017; Rausch et al., 2016)
	Decision support systems:
	➢ Modular suitability index integrated with the critical factors determining manufacturability, logistics and assembly (Salama et al., 2017) ➢ Managing information flow and design processes to reduce design risks in offsite construction projects (Sutrisna & Goulding, 2019) ➢ "minimization of the overall assembly geometric deviation, and (2) avoidance of rework caused by component aggregation. "(Rausch et al., 2016)
Back-end Issues	Manufacturability
	➢ Integrated prefabrication configuration and component grouping for resource optimization of precast production (Khalili & Chua, 2014)
	Metrics and Indices
	➢ Integrate the critical factors in manufacturability, logistics and assembly to the modular suitability index (Salama et al., 2017) ➢ Total fabrication cost and design deviation index (Said et al., 2017) ➢ Composite optimized assembly index and voting analytical hierarchy process (Gbadamosi et al., 2019)
	Supply-chain Management

	➢ (Hofman et al., 2009) ➢ Product modularity on supply-chain integration (Pero et al., 2015) ➢ Enhance supply network performance (Arashpour et al., 2017) ➢ Cost term and constant transfer term in production lead-time hedging (PLTH) (Zhai et al., 2016)

Front-end issues: Platform-based design methods are able to balance the commonality and the variety in industrialized housing production, which shares a common feature with automobile manufacturing (Gann, 1996). Implicit studies using product architecture for industrialized building can be dated back to 1990s, Japanese companies have deployed market specialists to represent customers in industrialized housing design and production, in which these specialist carried out market research through direct and indirect approaches with customers and clients (Gann, 1996). This brings another critical concept, project information flow induced by customers. The timing of customer involvement in the building design development may affect the production strategy. Similarly a decoupling point between planning and customer differentiates the production strategy (Barlow et al., 2003). Three types of production information flows were identified based on this (Winch, 2003). Thus the production information flow illustrated in the aforementioned case can be defined as new product development as only market research has been carried out and no actual customer relationship was established. And other two types of production information flows are tender and procurement on account of the integrity level of specification to satisfy customer needs (Winch, 2003). Design-to-order (DTO) or engineer-to-order (ETO) strategies are suitable for tender as substantial design development is required upon receiving the customer requirements. And concept-to-order (CTO) strategy applies to procurement if detailing of design is mature. Early attempts in parametric modeling in BIM can facilitate the cross discipline communication (Lee et al., 2006). For better information integration and developing a platform based design, a building information model (BIM)-based product architecture model (PAM) was established to manage the building components using a product-based design approach (Ramaji & Memari, 2015: p. 12). Ramaji et al. (2017) further developed this information integration platform as an information framework based on information delivery manual (IDM). This framework strengthened the inter-discipline information exchange by providing standard information to the right actors timely.

Design and development issues: How to interoperate functional requirements to product architecture is another critical issue in product platforms. Veenstra et al. (2006) employed the product platform structure to articulate the housing design and product development process following three steps, product architecture, interface and standards. In the first stage to capture the product architecture, modules and components were mapped according to the standard classification. And the interfaces were investigated via the design for variety method proposed by Martin and Ishii (2002). By comparing the metrics using generational variety index and coupling index in receiving and supplying specification flows, standardization of different modules can be optimized to better serve the platform (Veenstra et al., 2006). In industrialized housing construction, platforms in technical and process domains were also proposed to standardizing building product development (Lessing, 2006: p.187). Major purposes for such technical platforms are to reduce abortive work and complexity in design and facilitate the collaboration in different stakeholders at design stage. Jensen et al. (2012) applied the parametric models for configuration of building systems to improve the information exchange between designers/engineers, producers and customers. Different model viewers of engineering, production and customer can transfer the information flows to downstream and feedback the rules to upstream. Similarly, Wikberg et al. (2014) further proposed a modular architectural view method to link the customer requirements to the platform development. Such kind of design support system can transfer the information required from later stages to the initial design stage. Its great potential also lies in the operational stages.

To utilize metrics for assessing different building system platform is another research area. Salama et al. (2017) integrated the critical factors determining manufacturability, logistics and assembly to the modular suitability index for quantifying the competitiveness of different industrialized building. Post occupancy evaluation is expected to include for better customization. Isaac et al. (2016) applied the cluster algorithm and graph theory into BIM data model for design optimization in industrialized building. This optimization method can automatically break down building systems into prefabricated modules considering the rules related their repetition rate, interfacing connection number and renovation frequency. Khalili and Chua (2014) developed an integrated configuration decision support methodology against the requirements of manufacturing and assembly in prefabrication construction to support the design and production systems. Mixed integer linear programming (MILP) was used to improve the utilization of prefabrication molds during production.

Back-end issues: Current literature on this area still remains in an embryonic stage, and no systematic research has well covered in the back-end issues. Manufacturability (e.g. machining capacity) is one of the most common constraints in the design rationalization Austern et al. (2018). Despite to build such capability, design automation such as parametric-based approaches has been progressively benefited the also revealed in the rationalization process. Schmidt III et al. (2014) employed clustering and impact methodologies to analyze the building system architecture and changes respectively. The interdependences between building components were also articulated through a "Dependency Structure Matrix (DSM)" to show adaptability of the building system. Platforms can not only reduce the design effort, but also improve the productivity in productions (Jensen et al., 2013). Through a configurable design platform, the different construction methods can be assessed using product and process platform approaches through discrete event simulation on a bridge design and construction (Larsson et al., 2016). A process platform can support the supply-chain by systemizing the information and work flow (Lessing, 2006: p.171-172). Other areas stated in the back-end issues (Pirmoradi et al., 2014: p. 5-6) in platform based DfMA in industrialized building are not well covered in the current literature.

3. Propositions

3.1 Conventional DfMA Information Exchange

In the conventional DfMA of industrialized building, information exchange patterns are versatile and fragmented with regards to different building methods and production strategies. Different stakeholders exchange information through exchange models. Timing of customer involvement stimulates decoupling points for customer order and project information flow points for detailed specification (Jensen et al., 2012; Winch, 2003). Even though different production and supply-chain strategies may apply, information exchange patterns generally remain unchanged in conventional DfMA practice. Information exchange between different domain experts are not integrated and still rely on exchange models extensively. As summarized in Table 2, there is no integrated and comprehensive DfMA platform has been proposed or studied using the platform-based design methodology in industrialized building so far. Most of the literature only focus on limited areas in the platform development.

3.2 Platform-based DfMA Information Exchange

Table 3: Limitations of Conventional DfMA and New Opportunities in the Platform-based DfMA

	Limitations of conventional DfMA	Solutions in platform-based DfMA
Information Exchange Pattern	Random and fragmented	Integrated
Design Considerations	Only focus on one or several issues	Span from front-end issues, design development to back-end issues
Production Strategy	ETO	Closer engaged with supply-chain, ETO, CTO, etc.
Product Architecture	Various	Modular

Integrated design: The decision support and information exchange in ETO-based industrialized building among different domains is mostly achieved by providing exchange models with constraints. And the capacity requirements from manufacturing and construction are transferred in a later stage after receiving the preliminary architectural model worked out by the architect and engineer domains. "Silo" still exists in the design process even though periodical exchange can improve the communication between domain experts. Platforms can offer a vehicle to integrate the cross-domain information together. An integrated design platform can consist of information constraints from manufacturing, logistics and assembly in which enables a configure-to-order production and supply-chain integration. CTO is different from traditional ETO with its commonality to maximize the manufacturability and its variety for mass customization. Such a CTO-based platform can integrate with configurable product design and leverage the computational and optimization methods to rationalize the design. Even traditional ETO with integrated supply-chain can be further enhanced to become configure-to-order. It also demonstrates a greater capability for customization based on standard and modular components, compared with other supply-chain and production strategies (Jensen et al., 2012). Preliminary design and design development can be integrated once such information for specific projects are pre-defined. Similarly, CTO strategy embedded in platform-based DfMA can provide capacity for design and production teams to early plan for the standard components in which potentially induces shifting of the decoupling point towards planning (Barlow et al., 2003). Along with the emergence of advanced manufacturing (e.g. computer numerically controlled (CNC) fabrication) and design automation (e.g. parametric modelling), design rationalization has been developing in different forms in regards to its role in the design process integrated design approach can take advantages of simultaneous co-creation (e.g. with real-time design support methods (e.g. Austern et al. (2018)'s real-time rationalization).

Configurable product design: Product platforms have synthesized into scalable, modular and generational ones based on the product architecture (Zamirowski & Otto, 1999). We found there were few attempts to synthesize the product architecture for industrialized building. A modular platform is used to create variants through configuration of existing modules (Meyer & Lehnerd, 1997). A scalable platform facilitates the differentiation of variants that possess the same function with varying capacities (Simpson, Maier, & Mistree, 2001a). A generational platform leverages product life cycles for rapid next generation development (Martin & Ishii, 2002). One endeavor towards product platform development is to design product families in the way of "stretching" or "scaling" (Rothwell & Gardiner, 1990)". Integrated building products can be very complicated interfaces which has less chance to re-exist in repetitive standard platforms. In order to fit with the different projects on a same platform, building products can be designed in a configurable form. The platform-based DfMA is expected to show its great capacity for configuration management in early stage of design, which draws constraints and requirements from downstream supply-chain. It can combine CTO strategy to a global product architecture incorporated with function requirements to reduce design changes (Jensen et al., 2015b). Effective configuration management can offer informative change controls to other stakeholders in complex projects (Whyte et al., 2016). Parametric modelling in DfMA projects have demonstrated its effectiveness in prefabricated building (Yuan et al., 2018). With more flexibility shows in the product view method composed of the customer, engineering, production and site assembly processes, future research on IDM can consider mapping between different information constraints to configurable views for information exchange (Jensen et al., 2012). Information exchange in such design can be streamlined in an efficient way by reducing the manual interference (e.g. exchange models or requirements in IDM-MVDs).

Modular product architecture: Figure 1 shows a schematic modular product platform framework for industrialized building. In this framework, different assemblies (e.g. building module or integrated building component) can interact with other counterparts in an adaptive and responsive manner, by linking with the constraints from production systems. Modular or volumetric building has proved high modularity in assembly level. But the modularity at subassembly or higher (e.g. building layout design) levels can be a challenge for design due to limited flexibility induced by separated modules. Nevertheless, previous literature have found a modular product architecture shows the great flexibility to balance the commonality and variety in platform-based industrialized building (Jensen et al., 2015b) compared with the integrated and modular product architecture by (Ulrich, 1995). With more standardized interfaces, it can leave more room for making decisions towards customization.

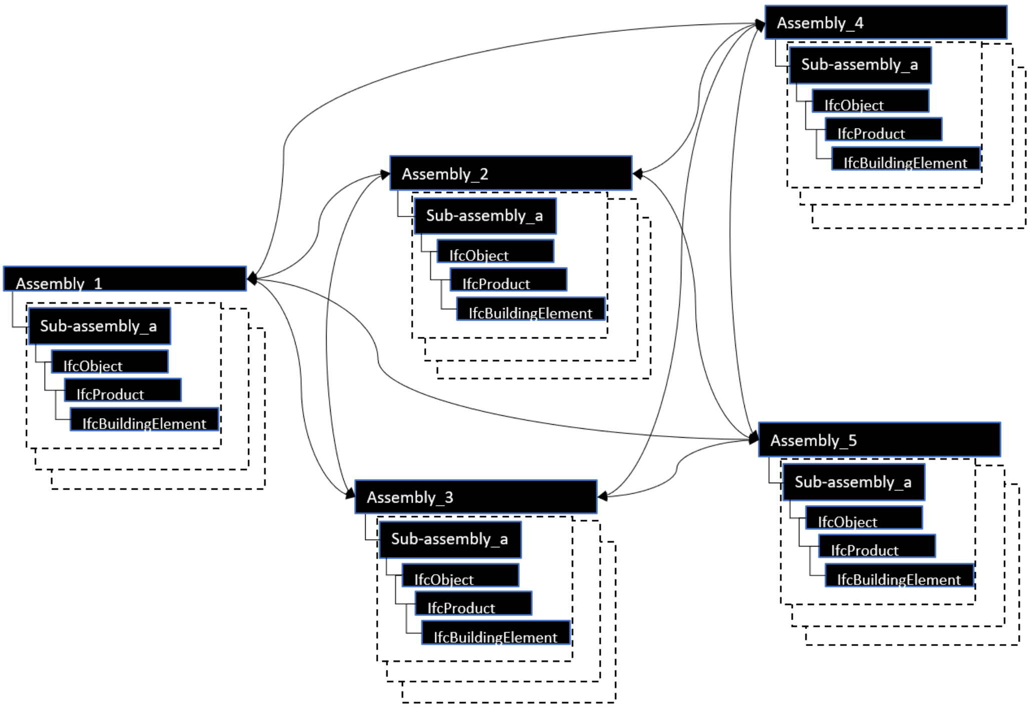


Figure 1: A Schematic IFC-based Modular Product Platform Framework through Configurable Design

4. Conclusions and Future Research

This research trajectory is important because it fills the gap between conventional and platform-based approaches of DfMA from an information exchange perspective. By summarizing and proposing the platform approaches in DfMA, potential benefits of design can be extended to the project lifecycle. More use cases of platform-based DfMA will be collected to validate the propositions drawn from this paper. Especially, to explore the information exchange in industrialized building by developing IDM and MVD is a key aspect for validation. Platform-based DfMA can incorporate decision making systems, metrics to show key features of building design as well as supply-chain management.

A platform for DFX has the capability to streamline other decision support systems to design stage and ensure the interoperability between different users and stages (Huang, 1996: p.6). One possible research area can be drawn on the real-time rationalization through simultaneous feedback and "parametric co-rationalization" between the design and manufacturing systems (Austern et al., 2018). Data-centric approaches like semantic techniques (e.g. linking BIM with product catalogues by Costa and Madrazo (2015)) and multi-objective optimization methods (e.g. Schmidt III et al. (2014)'s research) have shown potential benefits to support this research. There are also more opportunities to investigate the platforms' role in the industrialized building. Particularly, the technological platforms in the types of internal, supply-chain and industry types in regards to their different "constitutive agents", "interfaces", "accessible innovative capabilities" and "coordination mechanisms" (Gawer, 2014). The specific institutionalization of platforms for industrialized building is another key area for researchers to study.

The review and synthesis of the literature extend the knowledge of DfMA by linking construction, particularly industrialized building with product design and development platforms. Platforms in different contexts can effectively streamline the project lifecycle in certain ways, which need more evidence to support. Despite the emergence of modular platforms, an automobile-like generational platforms proposed by Zamirowski and Otto (1999), is yet to be developed. A study on this can potentially show the evolvement of building design practice. Novel design support systems can enable the rapid and iterative development of such platforms for industrialized building. To develop such systems needs an in-depth understanding of flexibility within platforms. Thus, it is worthwhile further studying using approaches of flexibility in engineering design.

Acknowledgements

The authors would like to acknowledge the support by the Centre for Systems Engineering and Innovation, Department of Civil and Environmental Engineering, Imperial College London.

References

Arashpour, M., Bai, Y., Aranda-mena, G., Bab-Hadiashar, A., Hosseini, R., & Kalutara, P. (2017). Optimizing decisions in advanced manufacturing of prefabricated products: Theorizing supply chain configurations in off-site construction. *Automation in Construction, 84*, 146-153.

Austern, G., Capeluto, I. G., & Grobman, Y. J. (2018). Rationalization methods in computer aided fabrication: A critical review. *Automation in Construction, 90*, 281-293.

Barlow, J., Childerhouse, P., Gann, D., Hong-Minh, S., Naim, M., & Ozaki, R. (2003). Choice and delivery in housebuilding: lessons from Japan for UK housebuilders. *Building Research and Information, 31(2)*, 134-145.

BCA. (2017). *Media Factsheets: Construction ITM Launch at SCPW, 24 October 2017*. Singapore: The Building and Construction Authority (BCA), Singapore

Berard, O. B., & Karlshøj, J. (2012). Information delivery manuals to integrate building product information into design. *Journal of Information Technology in Construction, 17*, 77-87.

Bralla, J. G. (1996). *Design for Excellence*. New York:: McGraw-Hill.

CLC. (2018). Smart Construction - a guide for housing clients.

Costa, G., & Madrazo, L. (2015). Connecting building component catalogues with BIM models using semantic technologies: An application for precast concrete components. *Automation in Construction, 57*, 239-248.

DEVB. (2018). *Construction 2.0: Time to change*. Hong Kong: Development Bureau (DEVB),

Dodgson, M., Gann, D. M., & Salter, A. (2008). *The Management of Technological Innovation: Strategy and Practice*: OUP Oxford.

Eastman, C., Sacks, R., Panushev, I., Aram, S., & Yagmur, E. (2009). *Information Delivery Manual for Precast Concrete*(

Eastman, C. M., Jeong, Y. S., Sacks, R., & Kaner, I. (2010). Exchange model and exchange object concepts for implementation of national BIM standards. *Journal of Computing in Civil Engineering, 24*(1), 25-34.

Emmatty, F. J., & Sarmah, S. P. (2012). Modular product development through platform-based design and DFMA. *Journal of Engineering Design, 23*(9), 696-714.

Gann, D. M. (1996). Construction as a manufacturing process? Similarities and differences between industrialized housing and car production in Japan. *Construction Management and Economics, 14*(5), 437-450.

Gawer, A. (2014). Bridging differing perspectives on technological platforms: Toward an integrative framework. *Research Policy, 43*(7), 1239-1249.

Gbadamosi, A.-Q., Mahamadu, A.-M., Oyedele, L. O., Akinade, O. O., Manu, P., Mahdjoubi, L., & Aigbavboa, C. (2019). Offsite construction: Developing a BIM-Based optimizer for assembly. *Journal of Cleaner Production, 215*, 1180-1190.

Hofman, E., Voordijk, H., & Halman, J. (2009). Matching supply networks to a modular product architecture in the house-building industry. *Building Research & Information, 37*(1), 31-42.

Huang, G. Q. (1996). *Design for X: Concurrent engineering imperatives*. London: Chapman & Hall.

IPA. (2018). Proposal for a New Approach to Building: Call for Evidence.

Isaac, S., Bock, T., & Stoliar, Y. (2016). A methodology for the optimal modularization of building design. *Automation in Construction, 65*, 116-124.

ISO. (2016). ISO 29481-1:2016 Building information models – Information delivery manual. In *Part 1: Methodology and format*: International Standard Organization (ISO).

Jansson, G., Johnsson, H., & Engström, D. (2014). Platform use in systems building. *Construction Management and Economics, 32*(1-2), 70-82.

Jensen, P., Larsson, J., Simonsson, P., & Olofsson, T. (2013). *Improving buildabuility with platforms and configurators*. Paper presented at the 21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013.

Jensen, P., Lidelöw, H., & Olofsson, T. (2015a). Product configuration in construction. *International Journal of Mass Customisation, 5*(1).

Jensen, P., Lidelöw, H., & Olofsson, T. (2015b). *Product configuration in construction* (Vol. 5).

Jensen, P., Olofsson, T., & Johnsson, H. (2012). Configuration through the parameterization of building components. *Automation in Construction, 23*, 1-8.

Jensen, P., Olofsson, T., Smiding, E., & Gerth, R. (2014). *Developing products in product platforms in the AEC industry*. Paper presented at the Computing in Civil and Building Engineering - Proceedings of the 2014 International Conference on Computing in Civil and Building Engineering.

Khalili, A., & Chua, D. K. (2014). Integrated Prefabrication Configuration and Component Grouping for Resource Optimization of Precast Production. *Journal of Construction Engineering and Management, 140*(2), 04013052.

Larsson, J., Lu, W., Krantz, J., & Olofsson, T. (2016). Discrete Event Simulation Analysis of Product and Process Platforms: A Bridge Construction Case Study. *Journal of Construction Engineering and Management, 142*(4).

Lee, G., Park, Y. H., & Ham, S. (2013). Extended Process to Product Modeling (xPPM) for integrated and seamless IDM and MVD development. *Advanced Engineering Informatics, 27*(4), 636-651.

Lee, G., Sacks, R., & Eastman, C. M. (2006). Specifying parametric building object behavior (BOB) for a building information modeling system. *Automation in Construction, 15*(6), 758-776.

Lee, Y.-C., Eastman, C. M., & Solihin, W. (2016). An ontology-based approach for developing data exchange requirements and model views of building information modeling. *Advanced Engineering Informatics, 30*(3), 354-367.

Lee, Y.-C., Solihin, W., & Eastman, C. M. (2019). The Mechanism and Challenges of Validating a Building Information Model regarding data exchange standards. *Automation in Construction, 100*, 118-128.

Lessing, J. (2006). *Industrialised House-Building Concept and Processes.* (Licentiate Licentiate Thesis), Lund University, Lund, Sweden.

Malmgren, L., Jensen, P., & Olofsson, T. (2011). Product configuration - Performance improvements of design work. *Journal of Information Technology in Construction (ITcon), 16*, 697-712.

Martin, M. V., & Ishii, K. (2002). Design for variety: Developing standardized and modularized product platform architectures. *Research in Engineering Design, 13*(3), 213-235.

Nawari, N. O. (2012). BIM Standard in Off-Site Construction. *Journal of Architectural Engineering, 18*(2), 107-113.

NIBS. (2007). *National Building Information Modeling Standard Version 1 - Part 1: Overview, Principles, and Methodologies* (3 ed.): National Institute of Building Sciences (NIBS).

Pero, M., Stößlein, M., & Cigolini, R. (2015). Linking product modularity to supply chain integration in the construction and shipbuilding industries. *International Journal of Production Economics, 170*, 602-615.

Pine, B. J. (1993). *Mass customization: the new frontier in business competition*. Boston, Mass.: Harvard Business School Press.

Pirmoradi, Z., Wang, G. G., & Simpson, T. W. (2014). A review of recent literature in product family design and platform-based product development. In T. W. Simpson, J. R. Jiao, Z. Siddique, & K. Hölttä-Otto (Eds.), *Advances in Product Family and Product Platform Design: Methods and Applications* (pp. 1-819).

Ramaji, I. J., & Memari, A. M. (2015). *Information exchange standardization for BIM application to multi-story modular residential buildings.* Paper presented at the Architectural Engineering National Conference 2015: Birth and Life of the Integrated Building - Proceedings of the AEI Conference 2015, Milwaukee; United States.

Ramaji, I. J., & Memari, A. M. (2016). Product Architecture Model for Multistory Modular Buildings. *Journal of Construction Engineering and Management, 142*(10).

Ramaji, I. J., & Memari, A. M. (2018). Extending the current model view definition standards to support multi-storey modular building projects. *Architectural Engineering and Design Management, 14*(1-2), 158-176.

Ramaji, I. J., Memari, A. M., & Messner, J. I. (2017). Product-Oriented Information Delivery Framework for Multistory Modular Building Projects. *Journal of Computing in Civil Engineering, 31*(4).

Rausch, C., Nahangi, M., Haas, C., & West, J. (2017). Kinematics chain based dimensional variation analysis of construction assemblies using building information models and 3D point clouds. *Automation in Construction, 75*, 33-44.

Rausch, C., Nahangi, M., Perreault, M., Haas, C. T., & West, J. (2016). Optimum assembly planning for modular construction components. *Journal of Computing in Civil Engineering, 31*(1).

RIBA. (2016). *RIBA Plan of Work 2013 Designing for Manufacture and Assembly*(

Sacks, R., Eastman, C. M., & Lee, G. (2004). Process model perspectives on management and engineering procedures in the precast/prestressed concrete industry. *Journal of Construction Engineering and Management, 130*(2), 206-215.

Said, H. M., Chalasani, T., & Logan, S. (2017). Exterior prefabricated panelized walls platform optimization. *Automation in Construction, 76*, 1-13.

Salama, T., Salah, A., Moselhi, O., & Al-Hussein, M. (2017). Near optimum selection of module configuration for efficient modular construction. *Automation in Construction, 83*, 316-329.

Schmidt III, R., Vibaek, K. S., & Austin, S. (2014). Evaluating the adaptability of an industrialized building using dependency structure matrices. *Construction Management and Economics,* *32*(1-2), 160-182.

Shahtaheri, Y., Rausch, C., West, J., Haas, C., & Nahangi, M. (2017). Managing risk in modular construction using dimensional and geometric tolerance strategies. *Automation in Construction, 83*, 303-315.

Simpson, T. W. (2004). Product platform design and customization: Status and promise. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM, 18*(1), 3-20.

Simpson, T. W., Jiao, J. R., Siddique, Z., & Hölttä-Otto, K. (2014). Epilogue - Product Family and Product Platform Design: Looking Forward. In T. W. Simpson, J. R. Jiao, Z. Siddique, & K. Hölttä-Otto (Eds.), *Advances in Product Family and Product Platform Design: Methods and Applications* (pp. 1-819).

Sutrisna, M., & Goulding, J. (2019). Managing information flow and design processes to reduce design risks in offsite construction projects. *Engineering, Construction and Architectural Management, 26*(2), 267-284.

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research Policy, 24*(3), 419-440.

Veenstra, V. S., Halman, J. I. M., & Voordijk, J. T. (2006). A methodology for developing product platforms in the specific setting of the housebuilding industry. *Research in Engineering Design, 17*(3), 157-173.

Webster, J., & Watson, R. (2002). *Analyzing the Past to Prepare for the Future: Writing a Literature Review* (Vol. 26).

Whyte, J., Stasis, A., & Lindkvist, C. (2016). Managing change in the delivery of complex projects: Configuration management, asset information and 'big data'. *International Journal of Project Management, 34*(2), 339-351.

Wikberg, F., Olofsson, T., & Ekholm, A. (2014). Design configuration with architectural objects: linking customer requirements with system capabilities in industrialized house-building platforms. *Construction Management and Economics, 32*(1-2), 196-207.

Winch, G. (2003). Models of manufacturing and the construction process: the genesis of re-engineering construction. *Building Research & Information, 31*(2), 107-118.

Wörösch, M., Hvam, L., & Bonev, M. (2015). Utilizing platforms in industrialized construction: A case study of a precast manufacturer. *Construction Innovation, 15*(1), 84-106.

Yuan, Z., Sun, C., & Wang, Y. (2018). Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. *Automation in Construction, 88*, 13-22.

Zamirowski, E. J., & Otto, K. N. (1999). *Identifying product portfolio architecture modularity using function and variety heuristics*. Paper presented at the In ASME design engineering technical conferences, DETC99/DTM-876, Las Vegas, NV.

Zhai, Y., Zhong, R. Y., Li, Z., & Huang, G. (2016). Production lead-time hedging and coordination in prefabricated construction supply chain management. *International Journal of Production Research*, 1-19.

Ontology-based modeling for construction site planning: Towards an ifcOWL semantic enrichment

Vito Getuli[1*] and Pietro Capone[1]
[1]University of Florence – Department of Civil and Environmental Engineering, Florence, Italy
* email: vito.getuli@unifi.it

Abstract

Nowadays, there is an increasing recognition of the value of effective information and knowledge management (KM) in the construction projects. Infact, Knowledge-based Process modelling is used in construction to support various simulation tasks. In this field, ontology-based semantic modelling is seen as an important means of addressing this problem to construct robust knowledge-based systems. In parallel, the advancement of information technology in the AEC industry makes available in a construction project a richness of design information offered by Building Information Modelling (BIM) IFC-based. The development of an ontological version of the IFC schema has been largely promoted and now the *ifcOWL* Ontology is available in the sector. But, in the construction scheduling task, BIM has progressively shown limits in terms of semantic representation and efficiency of supporting scheduling processes and for this reason this study, which is a part of a wider research project, aims to organize and formally represent by using ontologies the construction scheduling knowledge in order to define a complete Knowledge-Base (KB) able to allow the development of computer applications and automated reasoning mechanisms for construction scheduling. It consists of four sub-ontologies, including Construction *Scheduling* Ontology, Construction *Workspaces* Ontology, Construction *Time* Ontology and *Building* Ontology. In this paper the Construction Scheduling Ontology is extensively presented in terms of classes, relationships and axioms. Such an ontology has been converted in a script in OWL language by using *Protégé* that is an open-source platform to construct domain models and knowledge-based applications with ontologies. The developed construction scheduling ontology represents an ifcOWL semantic enrichment which is the first step towards automated knowledge-based scheduling systems integrated with BIM.

Keywords: Construction scheduling, Ontology-based modelling, ifcOWL, BIM

1. Introduction

The effective realization of building construction projects is closely linked to the construction activities scheduling process that should consider many factors such as the workspaces availability in site, according to their dynamic nature. Poor schedules estimate results in congested site areas, wasteful material movements, accidents and decline of productivity. In this context, from 1987 to 2005 few Expert Systems were setted such as *GHOST* (Navinchandra et al., 1988), *Construction Planex* (Zozaya-Gorostiza, 1989), *ConsPlans* (Kano, 1990), *BUILDER* (Cherneff et al., 1991), *FASTRAK-APT* (Lee et al., 1998), *CBRidge Planner* (Tah et al., 1999) and so forth. Their main subjects include coding activities, sequencing activities, representing schedules and levelling resources. They are automatic construction planners based on artificial intelligence techniques, precisely. Among all these, but also in other sectors, it has been proven that ontology-based expert systems are the most effective due to the fact they are based on a formal representation of the knowledge on which rule-based reasonings mechanism can be attached. These formal representations allow a coherent definition of objects, not only by describing their characteristics but also by the relationships that exist between them; so that we can express and share the meanings and structure of the material and immaterial concepts that belong to the construction scheduling domain of knowledge which is the subject of the presented research. What it was missing in those Expert Systems was the availability of a building information so use as input data in a standardized formal representation. In the recent years, with the increasing development of ICT, the AEC industry has available in a construction project a richness of design information offered by Building Information Modelling (BIM) by using the IFC-. The development of an ontological version of the IFC schema has been largely promoted in the sector and now the ifcOWL Ontology is available. But for what concern the construction scheduling task, the IFC data structure and the ifcOWL Ontology is very limited in terms of semantic representation to support construction scheduling processes. On this basis, this article propose a semantic extension of the ifcOWL ontology which allows the integration a knowledge-based able to represent the necessary knowledge to address the scheduling task.

2. Background: Ontology based modelling in AEC Industry

Modeling plays a significant role in representing the domain of construction process. In the construction industry, process modelling is used more to support simulation. In looking elsewhere, ontologies can provide a powerful modelling approach. As defined by (Gruber 1995), '*ontology is a formal representation of an abstracted view of a domain that describes the objects, concepts and relationships between them that holds in that domain for a stated purpose or concisely an explicit and formal specification of a conceptualization*'.

Nowadays, ontology-based modelling is central to many applications as largely explained in (Motta 2000), such as medical and biological systems, information management and integration systems, electronic commerce and web services and themselves are used within the realm of artificial intelligence to capture knowledge, and create a model of the knowledge Base. It has emerged that in the recent year the development of domain ontologies in the AEC Industry has been identifies as pivotal point to develop knowledge management and integrated workflows (Zhou et al., 2016). An overview is proposed below. (Lima, 2005) implemented the e-COGNOS platform testing the benefits of using semantic systems for adequate search and indexing capabilities. Another example is the ontology DOCK 1.0. It aims to develop a conceptual structure of key terms in the construction domain and their relationships and behaviour (El-Diraby, 2013). (Akinci et al. 2010) envisioned that semantic CAD/GIS web services can provide away to address the lack of interoperability between CAD and GIS platform. (Benevolenskiy et al. 2012) developed a distributed multi-model-based Management Information system for simulation and decision-making on construction project. The major challenge of the system was the management of the information and model logistics as well as the interdependencies among the application models. A domain ontology for construction concepts in urban infrastructure products was developed by (Diraby 2011). (Wang and Boukamp 2011) presented a framework aiming to improve access to a company's JHA knowledge by using ontologies for structuring knowledge about activities, job steps, and hazards. (Zhong et al. 2012) developed an ontology-based semantic modelling approach of regulation constraints based on proposed CQIE ontology and construction process. Recently, (Zhang et al. 2015) investigated a new approach to organize, store and re-use construction safety knowledge. A construction safety ontology is proposed to formalize the safety management knowledge. Finally, in order to understand how other fields, which have high-level scheduling approaches, addressed the problem of scheduling activities and resources, Tab. 1 groups the most important reviewed studies.

Table. 1 Summary of the review of the scheduling ontologies developed in other research fields

Scheduling Ontology Studies	Object	Construction Field	Other fields	Generic	Specific	Integration with other ontologies	Toolkit Integration
Scheduling Task Rajpathak et al. (2000)	Scheduling Cost Control			•		Time	•
OZONE Smith et al. (1997)	Logistic Scheduling		• Transportation logistics				•
Kasis-Sophina Hori et al. (1995)	Generic scheduling		• manufactory				
CommonKADS Gobin and Subramanian (2009)	Scheduling		•	•			
COMIREM Smith, et al. (2005)			Crisis-action logistics planning	•			
Job Assignment Ontology Rajpathak (2001)	Scheduling		•		•		•
Industry Foundation		•			•	Building Structure	

Classes (IFC) BuildingSmart (2004)					
Mephisto **Lambert and Nowak (2009)**		Military and national security domains	•		
OnSITEsimu Proposed in this research	•		•	Time Space Building	•

3. Research objectives and method

The **main goals** of the presented research work are:

1. To formalize construction site planning knowledge; that means to identify relevant concepts and main items, also called entities, in construction site, as well as their attributes and interrelationships. Such an ontology consists of a **Knowledge Base** (KB) to wrap the existing product model in construction, the so-called Industry Foundation Classes (IFC) which doesn't contain such a knowledge representation by now;

2. The ontology should support a fuller semantic representation of construction site activities in terms of: (a) Resources and site workspaces, (b) Planning and Scheduling Constraints;

3. To implement such an ontological structure in a computer interpretable language in order to use it in future work to link information from different knowledge domains, to attach automated reasoning mechanisms and use such a KB as core schema for software applications for construction site planning and scheduling linked to a BIM Model;

The Knowledge Base was coded by using four sub-ontologies, listed below that have been considered fundamental for representing construction site knowledge:

i) *Construction* ***Scheduling*** *Ontology*: this sub-ontology contains all those elements for representing the construction scheduling problems and constraints. It provides a structural foundation for analyzing the information requirements of a construction schedule which should be depend on availability and typology of resources, on space-temporal constraints, on allocation of workspaces.

ii) *Construction* ***Workspace*** *Ontology*: it contains the site workspaces representation and the properties Infact, workspaces need to be represented with their basic geometrical and capacity properties and need to be linked to the building objects.

iii) *Construction* ***Time*** *Ontology*: it is the ontology of temporal concepts for describing temporal properties of site entities in their evolution across time. It also objects to describe possible relations between time periods in order to define the temporal positions among activities, workspaces and building objects. It plays a pivotal role in developing rule-based reasoning mechanisms for minimize overlapping activities in terms of workspaces.

iv) *Construction* ***Product*** *Ontology*: This sub-ontology represents the domain of Building Information Models (BIMs) and it describes the functional, geometrical and topological information of the building objects –products- that the Knowledge Base needs to get in order to activate reasoning mechanisms in future software applications.

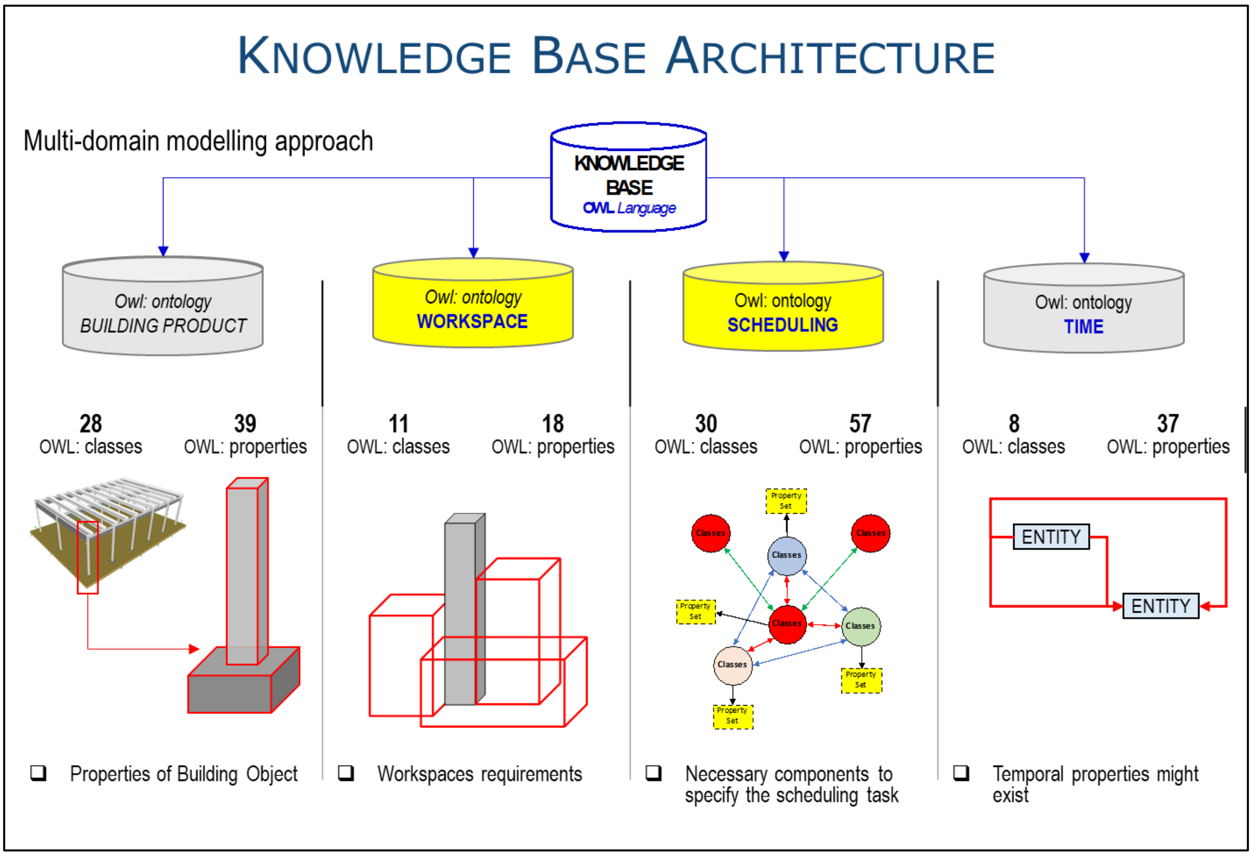


Figure 1: Virtual Reality training protocol application process and data flow

4. Ontology computerization

To make the Knowledge Base machine-interpretable, in this research, we have chosen OWL, the *Web Ontology Language*, to compute the ontologies (Baader et al., 2003). The reasons of this choice are twofold:

a. As before mentioned, BIM systems and models are equipped with a standardized interface for data exchange which is the IFC (Industry Foundation Classes) standard (OpenBIM, 2016). Pilots schemes in academic research have tried to make IFC available as an OWL ontology to allow the usage of semantic web technologies as explained in (Drogemulle and Schevers 2005) and (Beetz (2009). Thanks to these research efforts, it is only a short while since the **ifcOWL ontology**, which is precisely meant to be used to allow extensions towards other structured data sets, is available. This would mean that a practical data-exchange between a given BIM and our KB (ontologies) can be established.

b. The possibility that the Knowledge Base can be able to rely on the ifcOWL ontology which underpins a BIM, would accomplish higher robustness. That way it would also be possible to link and provide our modelling domain (classes, relationships and properties) with the logical and geometrical relationships between building objects that are contained within the BIM ontology (ifcOWL).

Based on these modelling assumptions, the **Construction Scheduling Ontology**, one of the four ontologies that constitute the KB (Figure 1) is presented. The others three ontologies will be presented in an extended publication.

Building an OWL ontology, the Construction Scheduling Ontology means to consider the formal description of concepts (**OWL classes**) in charge of simulate both construction activities and scheduling problem referred to them. Each concept, within the ontology, is described by using various relationships with other concepts or attributes (**OWL properties**) and restrictions on properties (**OWL restrictions**).

More precisely 'OWL properties' are *binary relations* on classes and there are two main types of properties:

- **Object-properties**. They are relationships between two classes or individuals.
- **Datatype-properties**. They link an individual to a Datatype-value (e.g., real number, decimal number, string, Boolean value, time instance, etc.).

Moreover, OWL allows the meaning of properties to be enriched using *property characteristics* (i.e., *functional* -FU-, *inverse* -IN-, *transitive* -TR-, *symmetric* -SY-, *asymmetric reflexive* -AS-, *irreflexive* -IR-). These textual abbreviations will be used in the ontology specification.

It is evident that classes are the cornerstone of the ontology. In this regard, the ontology visualization can help by assisting in the development, exploration and verification of themselves. Although several computerizations for ontologies have been developed in the last couple of years.

In this research *Protégé* was used as open-source platform to construct knowledge-based applications with ontologies. The Visual Notation for OWL Ontologies –VOWL- has been chosen to represent ontologies in this research (Lohmann et al., 2014). The representations are based on graphical primitives and colour scheme; a selection is shown in the Figure below.

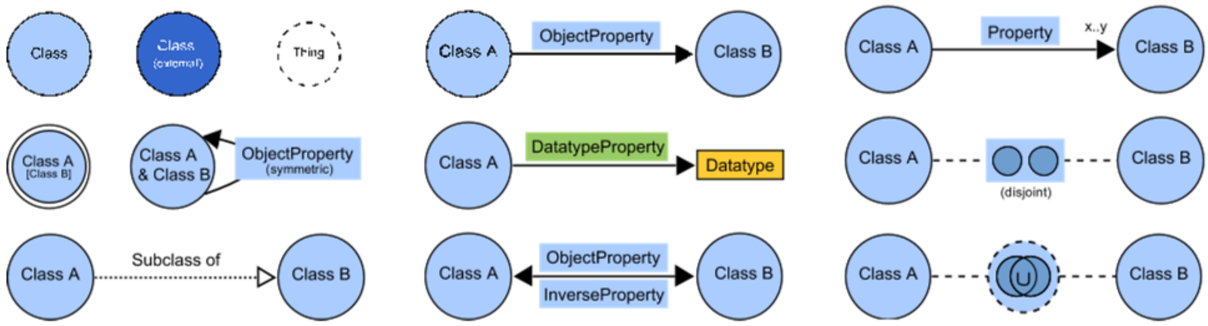


Figure 2: Selection of visual notions to represent ontologies after developing a specific script in OWL language (Lohmann, 2014)

5. Overall framework of the Scheduling Ontology

In the proposed scheduling framework, the ontology can be formally represented as a mapping from a *twelve-dimensional* space (classes). Such an input parameter provide the necessary components to specify the scheduling task.

1. **Construction Method**, (CM) = {cm_1, ..., cm_n}. This class is an abstract entity which describes the construction work execution. This entity drives the ontology. The construction schedule, linked to a given Building Information Model, should have Construction Methods as much as the number of Object types.

2. **Work Description**, (WD) = {wd_1...., wd_n}. It describes the construction execution referred to a given Construction Method, its spaces and resources on site by using generic terms.

3. **Demand**, (De) = {de_1, ..., de_n}. This class contains both construction procedures and safety rules that are formally and graphically simulated by using the 'workspace ontology'.

4. **Construction Product**, (CP) = {cp_1, ..., cp_n}. This class comprises all the building objects that are primarily part of the construction of the building itself. Its categorization comes directly from the IFC-schema as later described in *Chapter 7*. Hence, the *ifcBuildingObjects*, contained in a given BIM, are converted in individuals that are referred to as being instances of the class 'Construction Product'.

5. **Condition**, (Cn) = {co_1, ..., co_n}. This abstract entity describes condition that must be achieved at the beginning (pre-condition) or ending (post-condition) of a Construction Method. A Condition can be expressed in terms of activities or milestone in a time period.

6. **Resource**, (Re) = {re_1, ..., re_n}. To define a Construction Method, it is necessary to choose specific Resources with a specific proposed-set. Semantics and properties of those resources vary according to the type of Resource and define their available capacity across time. A number of resources have

been proposed which should be cover those required by a construction process.

7. **Constraint**, (Cs) = {co_1, ..., co_n}. Getting the Expert System to work on the solution to the given scheduling problem, constraints determination and satisfaction is essential. Generally, a constraint restricts the set of values that can be assigned to a given variable according to (Smith et al. 2005). Our scheduling domain provides the means to model three types of constraints that restrict the assignment of Start and End-Times and the physical allocation in site of Resources and Workspaces related to each construction activity:

   a) **Resource-depended**. It designates the condition under which a Resource (e.g., scaffolding, labor crew, etcetera) can be assigned to a given construction activity or restrict the physical capabilities of resources to handle more activities simultaneously;

   b) **Time-depended**. It defines the possible relations between objects within the construction process (e.g., *before*, *meets*, *overlaps*, *during*, *equals*, etc.) and their time periods;

   c) **Space-depended**. It consists in a family of three sub-constraints which are strictly connected to the workspace simulation (e.g., equipment space, labor crew space, hazard space, etc.) and all those constraints which can be automatically extracted by the IFC Building Structure (e.g., if workspaces of two activities overlap, they can't run simultaneously in construction site).

   Moreover, a further classification of constraints has been introduced:

   d) **User-setted**. They derive directly from the user specifications depending on his experience who directly could add constraints;

   e) **System-setted**. Those ones that are automatically generated by the ontological structure due to properties assigned to the relationships;

   f) **Building-setted**. They derive directly from the BIM by using transformation rules (e.g., a beam should be constructed after connected columns);

   g) Simulation-setted. Those ones that derive from the 'workspaces conflicts checking process'.

8. **Phase**, (Ph) = {ph_1, ..., ph_n}. A group of strongly-related construction processes defines a Phase which ends with a Milestone.

9. **Process**, (Pr) = {pr_1, ..., pr_n}. A process represents the most abstract class that groups various activities.

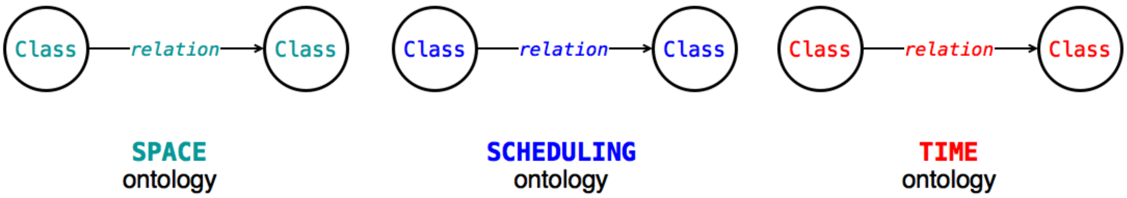
10. **Activity**, (Ac) = {ac_1, ..., ac_n}. In the proposed architecture, a schedule is represented as a network of Activities that will produce a number of Construction Products by using workspaces. To schedule an Activity, it is necessary to choose Resources that produce the time intervals to assign to

each activity depending on their capacity level.

11. **Milestone**, (Mi) = {mi_1, ..., mi_n}. A Milestone represents a Phase finalization connected to a given Time Instant.

6. Topological structure

Here, it is depicted the framework models of the scheduling ontology in terms of the main classes, properties and relations diagrams. To enhance a better explication, in body of the text that follows, a different font has been used for ontological objects and the font color is used to distinguish the belonging to one ontology that composes the Knowledge Base (Figure below).



Core class of this ontology is ConstructionMethod. This is due to the fact that other classes depend on it. Infact by using relationships and properties, listed below, each construction method is described in terms of required resources, activities and workspaces. All these classes are inextricably linked in an intelligent framework.

Therefore, a ConstrucitonMethod *produces* or *consumes* a number of Construction Products. The class ConstructionProduct contains a list of individuals which represent the building elements and their information requirements, such as columns, beams, slabs and walls, and provide the main interface for connecting the scheduling problem to the given BIM. It follows the structure of the IFC schema and mainly includes sub-types of *IfcBuildingElement*. This building elements include major functional parts of a building.

The binary relationship between Construction Methods and Construction Products is chosen by the user. A Construction Method presumes some Condition could be existing before (*precondition*) or after (*postcondition*) the given Construction Method runs within the construction site. A Construction Method *isDescribedBy* a WorkDescription which specifies the construction execution describing allocation of spaces and required resources by using generic terms. A WorkDescription is regulated by a procedural guideline which is specified in the class Demand by using a set of principles or conditions which can define a procedure or a SafetyRule. This means that if the user links two workspaces to a construction method the system automatically classifies this relation as a procedure of the Construction Method or as a safety rule if a safety or hazard space is included. Each procedure or safety rule contained in a Demand *requires* a number of Resource.

The class Resource is also central to the definition of our scheduling ontology. It represents an entity which is assigned to a Construction Method for its execution. Each Resource can *handle* one or more activities simultaneously and is provided by a specific property set. These properties are all those which effect its availability and utilization in function of its specific Capacity (e.g., *hasCapacityLevel*). Making efficient use of Resources, in supporting activities, becomes the one crux of the scheduling problem which is managed by the rule-engine. A resources class hierarchy has been proposed which models each sub-class in terms of its dynamically changing amount of *CapacityLevel*. The class hierarchy is explained in Figure 4 and the main class restrictions which are modelled are depicted in Figure 5.

Going on, an Activity *isFollowedBy* an interrelated set of sub-activities. To define a schedule, each Activity requires MicroLevelWorkspaces (entities of the Workspaces Ontology) to being performed in site. A Process is modelled as an abstract entity which *isComposedOf* a number of Activities. More Processes make up a Phase which ends with a Milestone and requires MacroLevelWorkspaces (entities of the Workspaces Ontology) to being performed within the construction site. Finally, a Milestone involves one or more ConstructionProduct.

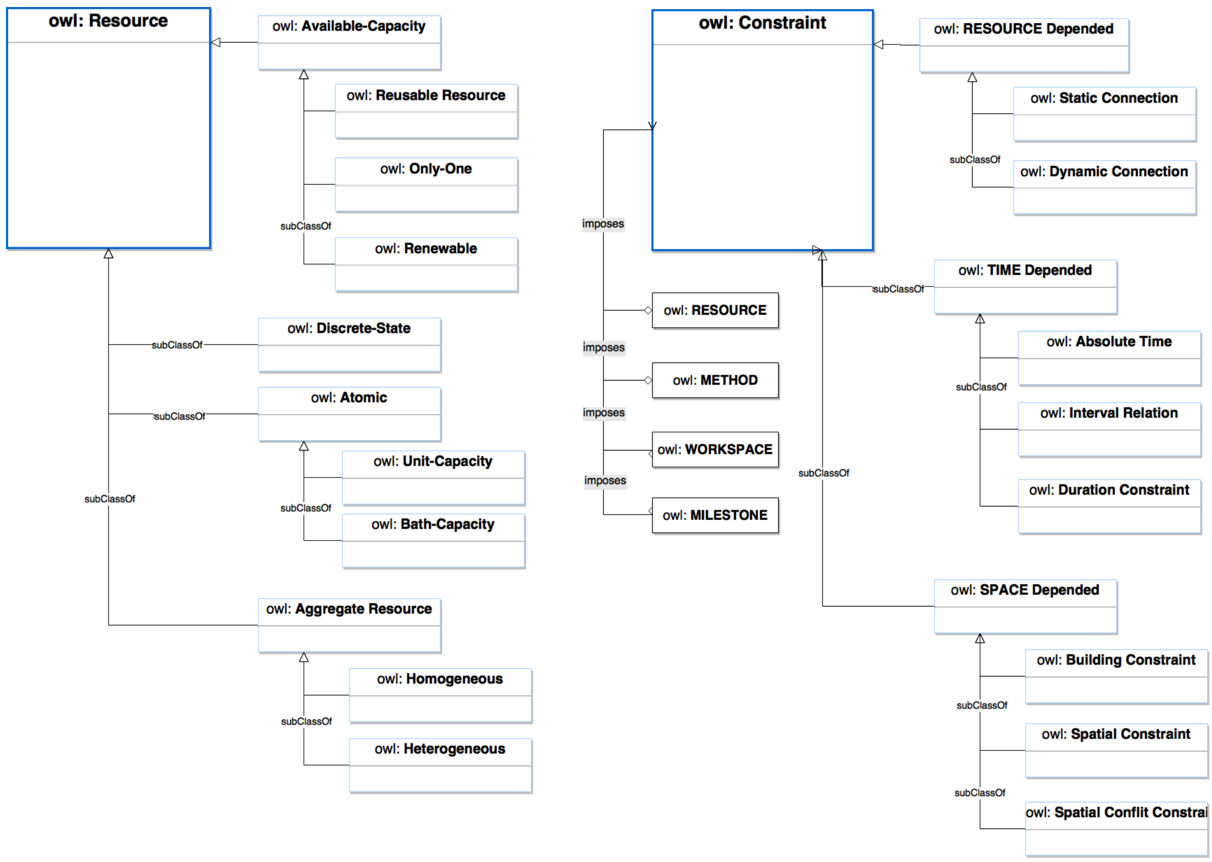


Figure 4: Class hierarchy in the construction scheduling ontology: resources types on the left side and constraints types on the right side

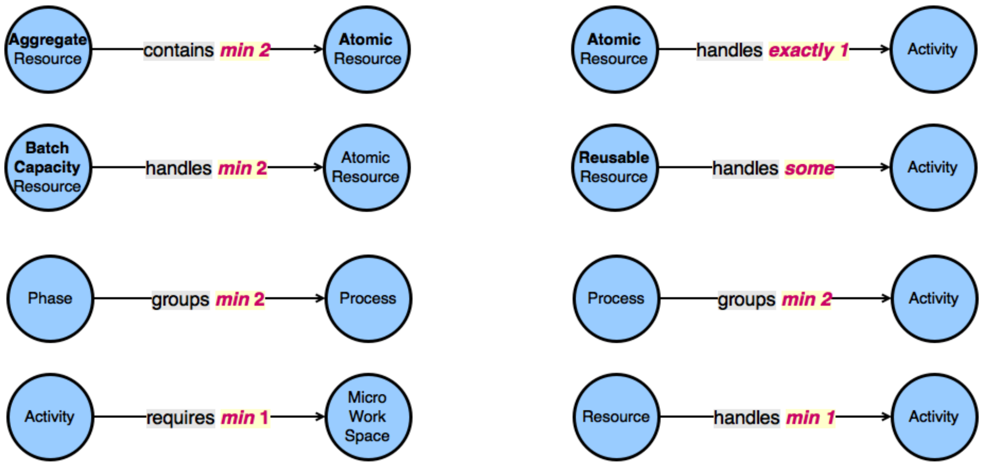


Figure 5: OWL classes restrictions as regard the scheduling ontology

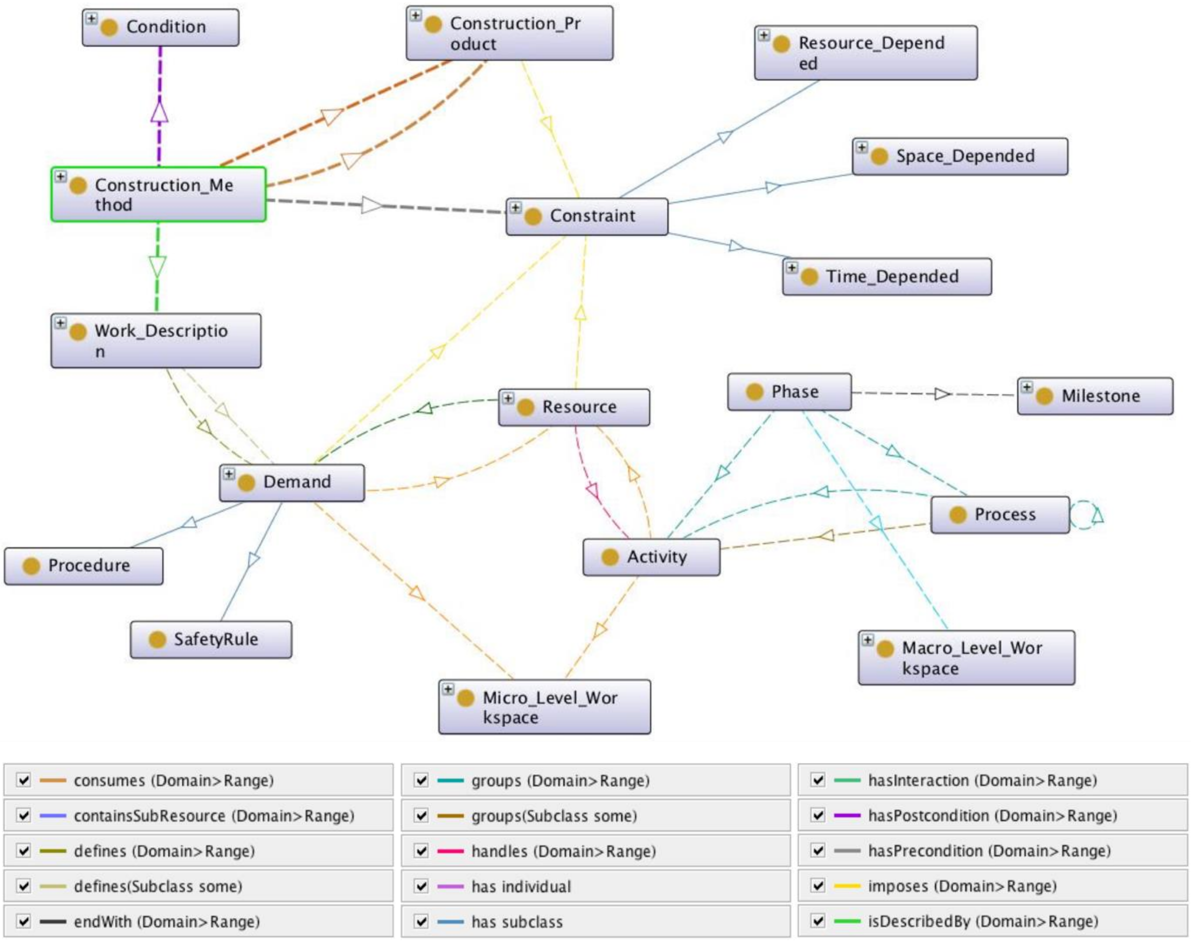


Figure 6. Visualization of the dynamic graph representing classes and relations of the Construction Scheduling Ontology. It derived automatically from the script in OWL and visualized in Protégé.

References

Navinchandra, D., D. Sriram, and R. Logcher. 1988. “GHOST: project network generator.” Journal of Computing in Civil Engineering (ASCE) 2 (3): 239-254.

Zozaya-Gorostiza, C., C. Hendrickson, and D., R. Rehak. 1989. Knowledge-Based Process Planning for Construction and Manufacturing. Academic Press.

Cherneff, J., M., R. Logcher, and D. Sriram. 1991. “Integrating CAD with construction-schedule generation.” Journal of Computing in Civil Engineering (ASCE) 5 (1): 68-84.

Lee, K., J., H., W. Kim, J., K. Lee, and T., H. Kim. 1998. Case and constraint-based project planning for apartment construction. Vol. 19. 1 vols. AI Magazine.

Tah, J., H., M., V. Carr, and R. Howes. 1999. “Information modeling for case-based construction planning of highway bridge proj- ects.” Advances in Engineering Software (Elseiver) 30 (7): 495-509.

Zhou, Z., Y., M. Goh, and L. Shen. 2016. “Overview and Analysis of Ontology Studies Supporting Development of the Construction Industry.” J.ournal of Computing in Civil Engineering (ASCE).

El-Diraby, T., and h. Osman. 2011. “Automation in Construction.” A domain ontology for construction concepts in urban infrastructure products 20 (8): 1120–1132.

Zhang, S., F. Boukamp, and J. Teizer. 2015. “Ontology-based semantic modeling of construction safety knowledge: towards automated safety planning for job hazard analysis (JHA).” Automation in Construction (Elseiver) 52: 29–41.

Zhang, S., J. Teizer, N. Pradhananga, and C., E. Eastman. 2015. “Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning.” Automation in Construction 60: 74-86.

Zhong, B., L. Ding, H. Luo, Y. Zhou, Y. Hu, and H. Hu. 2012. “Ontology-based semantic modeling of regulation constraint for automated construction quality compliance checking.” Automation in Construction (Elsevier) (28): 58–70.

Smith, S., F., and M., A. Becker. 1997. “An Ontolgy of Constructing Scheduling Systems.” AAAI Symposium on Ontological Engineering. Stanford: AAAI Press.

Smith, S., F., G. Cortellessa, D., W. Hildum, and D., W. Ohler. 2005. “Using a scheduling domanin ontolgy to compute user-oriented explanations.” Planning, Scheduling, and Constraint Satisfaction: From theory to Practise.

Lambert, D., and C. Nowak. 2008. “The Mephisto Conceptual Framework” Command, Control, Communications and Intelligence Division DSTO Defence Science and Technology Organization. Australia.

Buildingsmart. 2014. Industry Foundation Classes Release 4 (IFC4). http://www.buildingsmart-tech.org/ifc/IFC4/final/html/link/structural-connectivity.htm.

Horrocks, I. 2004. SWRL: A Semantic Web Rule Language Combining OWL and RuleML. https://www.w3.org/Submission/SWRL/.

Horrocks, I., P., F. Patel-Schneider, H. Boley, S. Tabet, B. Grosof, and M. Dean. 2004. SWRL: A semantic web rule language combining OWL and RuleML.

IDLab, Ghent Univeristy's. 2013. IFC-to-RDF converter. IDLab. https://github.com/IDLabResearch/IFC-to-RDF-converter/wiki/IFC-to-RDF.

Engineering Design & Collaboration Technologies

Location Referencing Families: A New Theoretical Framework

Russell Kenley[1], Toby Harfield[2, *], Robin Drogemuller[3], David McMeekin[4] and Petra Helmholz[4]
[1]Swinburne University of Technology, Melbourne, Australia
Unitec Institute of Technology, Auckland, New Zealand
[2]Swinburne University of Technology, Melbourne, Australia
[3]Queensland University of Technology, Brisbane, Australia
[4]Curtin University, Perth, Australia
[*]email: tharfield@swin.edu.au

Abstract

This conceptual paper provides a new theoretical framework for location necessary to enable integration of current road asset management systems with digital designs based on IFC standards. The purpose of the critical literature review was two-fold; first to find instances of the term ‘location’ and second to find definitions that apply to current and future use, specifically for road asset management. Three important concepts are proposed. The first is redefining the meaning of location data taking into account three different types of model view: linear/network location referencing methods, spatial earth coordinates, and digital design modelling. The creation of new families for location referencing methods takes into account these model views. The new families proposed are: Topological (Logical Linear and Network Referencing), Geospatial (Real World Coordinates), and Geometric (Model Coordinates). By expanding the definitions of each of these families, a more complex, and thus, more inclusive concept of location data can be utilized to support the storage and retrieval of both heritage and future road asset location information.

Keywords: Location Referencing Families, Topological, Geospatial, Geometric

1. Introduction

Globally, road assets are a major responsibility. Approximately 40 million kms of roads in 222 countries have been built and now must be maintained. Simple maintenance becomes more difficult for two reasons; (1) the increased number and types of vehicles using the roads and (2) the ever-increasing costs for repair due to the increasing intensity of major weather events. Thus, the escalating costs drives the need for more effective and efficient ways of managing road asset budgets.

However, the technologies that could enable the solution are still evolving. Therefore, a conceptual discussion of the problems and possible solutions may provide a framework that could be used. That is the purpose of this paper. To facilitate the discussion, this paper focuses on one important implementation issue: location referencing methods for road asset management.

Location Referencing Methods (LRMs) are a fundamental feature of road asset management systems LRM generated location data may be collected from a number of sources and in a number of different formats. However, currently there is no theoretical framework to integrate the location data from past or present referencing methods. Therefore, the objective of this paper is to fill the theoretical gap concerning types of location referencing methods required for the road asset management transformation in the 21st century.

In order to understand the problem, a desktop critical review explored 120 documents. The extensive review focused on the location referencing requirements of road asset management. This included international standards that underpin current specifications. Analysis of the documents showed that, globally, individual jurisdictions have developed a wide variety of LRMs. However, the similarity of properties suggested the concept of clustering the variety of types into families of LRMs, especially because of the number of papers discussing 'future data sources' (Kenley and Harfield, 2018).

The balance of the paper outlines the findings of the critical review. Section two provides an description of the research method. Section three describes the proposed alternative set of conceptual families; Topological, Geospatial and Geometric. Details of each of the families are provided in sections four, five and six. The Conclusion summarizes the reasons that the new conceptual framework is required for road asset management in the 21st century.

2. Critical Review

The purpose of the critical literature review was two-fold; first to find instances of the term 'location' and second to find definitions that apply to current and future use. The first step was to do a content analysis of a sample of 120 documents. The content analysis criteria were:

- The **purpose** of the document
- **Perspective of the writer** and the expected reader of the document in relation to location referencing depending on the specific asset life-cycle phase
- **Asset type**: road networks, transport systems or networks comprised of multiple asset types
- **End uses** for a location model, each with its own sub-categories. The uses of location included:
    - way finding (specific addresses, co-ordinates, etc.)
    - works & services (network service lines, proximity regions, resources optimisation, maintenance, works & services co-ordination, construction phase planning, etc.)
    - road users (public information, traffic information, haulage, road closures, flood & fire alerts, legal & registration, etc.)
    - co-operation with utilities (telecommunication, water, etc.)
    - future of roads (automated vehicles, GIS, BIM, etc.)

Summaries of each of the content analysis criteria were then considered in terms of location data utilisation. For the purposes of this paper, the review found that one content sub-set identified is Location Referencing Methods.

Table 1 provides an example of some of the documents that provide a definition of a location referencing method.

Table 1: Location referencing method definitions from a variety of sources.

Source	*Year*	*Definition of Location Referencing Methods (LRMs)*
T Ries	*2000*	*A way of describing the location of an object relative to some known point in space.*
HTC, TNZ Task 2100, Glossary	*2001*	*The technique used to identify the specific point (location) or segment of road, either in the field or in the office.*
NCHRP Report 460, Glossary	*2001*	*A mechanism for finding and stating the location of an unknown point by referencing it to a known point.*
ISO 19133	*2006*	*The manner in which measurements are made (and optionally offset from) a curvilinear element.*
Austroads AP-T190-11	*2011*	*The method used to identify a specific point or event on the road by providing it with a unique address.*
ISO 19148	*2012*	*Manner in which measurements are made along (and typically offset from) a linear element.*
ISO 17572	*2015*	*Methodology of assigning location references to locations.*

This critical review found that meanings vary between standards, government or industry reports, and academic papers as shown in table 1. Indeed, variation is the driver of the necessity for the new theoretical framework.

3. Defining a Three Family Theoretical Framework

In a paper published in 2000, Ries identified three groups of LRMs: geodetic, geometric, and linear (Ries, 2000). Although Ries proposed three groups and definitions (table 2), he also recognized the attributes of a number of sub-sets within each group.

Table 2: Definitions of Ries' location referencing methods groups.

Type	*Location Referencing Methods that:*
Geodetic (Geographic)	*describe locations on the earth's surface*
Geometric	*represent discrete features on the earth as a map coordinate*
Linear	*describe locations along discrete network features*

The importance of the sub-sets is that they can be conceptualized as families of location referencing methods. Thus, providing a framework for different types of location referencing methods for road asset management (Ebendt and Tcheumadjeu, 2017).

In 2000 Ries was taking into account the growing dependence on new spatial technologies for asset management. His location referring method groups have either a linear or a spatial focus, and more importantly, a combination of both. Indeed, during the last 20 years road network asset management functions have come to require both linear and spatial LRMs as Ries suggested they would.

However, more recently scholars suggest that emerging digital technologies, such as BIM (3D, information loaded, digital design) (Steel et al., 2012) should also be incorporated into the future functionality of road asset management.

The belief that these technologies will drive changing requirements for future road asset management performance (CEDAR, 2018), means that an expanded framework of location referencing methods is required. That is the purpose of the proposed theoretical framework outlined in this paper.

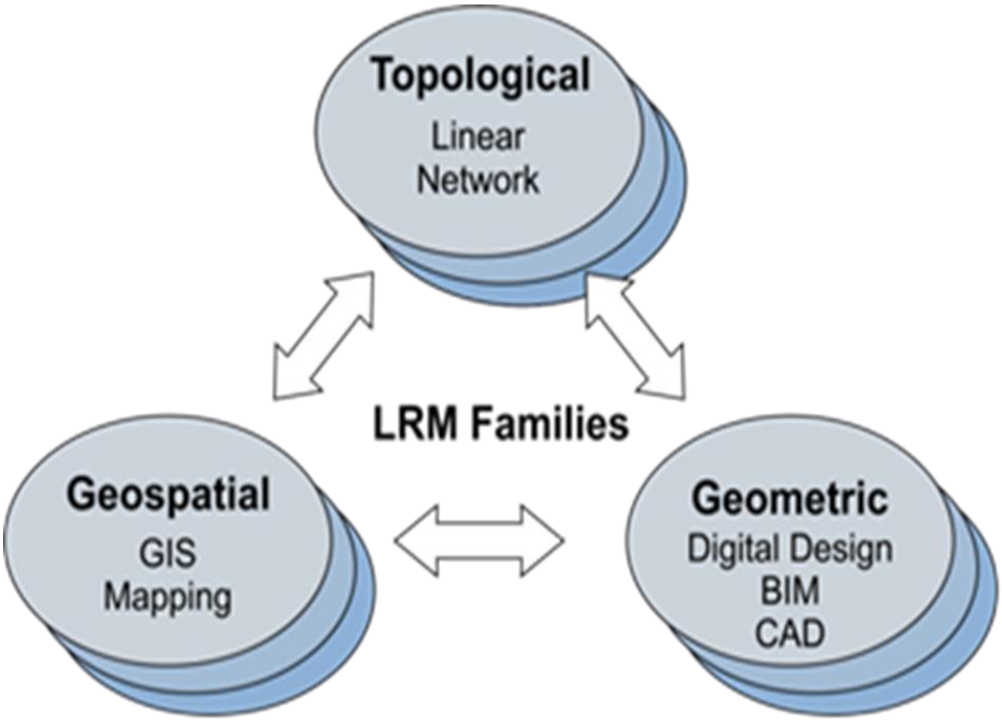


Figure 1: Proposed families of location referencing methods

4. Family One: Topological (Linear/Network)

The two groups of LRMs within the Topological family are:

- Linear referencing (discrete linear elements)
- Network referencing (a topologically connected routable network of linear elements).

4.1 Linear referencing

Many studies of linear location referencing methods provide the wide variety of referencing methods for road infrastructure asset management (Kenley & Harfield, 2018; HTC, 2001; NCHRP 2001). They are a group of methods that, at the base level, describe locations relative to a one-dimensional object, measured along (and optionally offset from) that object (ISO19148, 2012). This group of LRMs does not rely on spatial coordinate information, but spatial coordinate information can be included as an attribute.

An extensive review used linear referencing methods is found in the 2001 report for Transit New Zealand (HTC, 2001). The report outlines 14 examples from US states and four examples of Australian states. The authors provide the advantages and limitations of the linear reference methods reviewed. This report clearly outlines the difficulty of any standardisation process because of the extensive variety of location referencing methods.

The main reason for the LRM variety is the differing business drivers for the local conditions within which roads are built and maintained (Kenley and Harfield, 2018). This will cause a long-term problem, because these legacy practices are also embedded in legacy asset management systems making up-grading difficult.

4.2 Network referencing

However, it is also possible to hybridize the linear location referencing methods by including geospatial data as attributes (particularly with modern geospatial databases such as Oracle Geospatial (Oracle Docs, 2019).

The international standard, ISO 17572-1 requires that location referencing methods should also enable referencing of the relative spatial relationship of objects and, more importantly, not change topological relationships by its own action (ISO17572, 2015). For example, the order of points along a line should not get confused.

The network referencing standard ISO19133 explicitly recognizes that the links and nodes of a road system are complex, interconnected and may be routable (ISO19133, 2016). Constructing a routable path in a road network may also require significant information other than the information provided by the location referencing methods. For example, addition information could include: grade separation, traffic flow direction, or turn restrictions. These may have both physical and temporal dimensions.

A routable path also requires location attributes such as: road class, road purpose, and environmental conditions. Some networks may also have complex 3D geometry, such as slope gradients for road and rail, or drainage networks. Thus, network referencing has been included in the more recent transport standards (ISO17572, 2015; CEN/TS16157, 2011).

4.3 Importance of topological location referencing

Topological networks provide the same advantages as linear referencing for human cognitive models (Lobben, 2004; Committeri et al., 2004; Choocharukul et al., 2002). However, they also provide a method for solving problems relating to routes or journeys. The obvious use is for journey guidance, such as navigation systems. ISO 19133 (2016) defines a navigation as "combination of routing, route transversal [changing] and tracking".

At the same time, for asset management, a more critical use of topological networks is for service delivery management (SA, 2019). Network service performance is central to the concept of road user service. This requires current-time analysis based on routes or journeys providing the possibility of alternative paths in the event of planned or unexpected disruptions, such as road works or accidents provided through all road asset management systems (Kazemi and Forghani, 2016; Roess and Prassas, 2014).

5. Family Two: Geospatial (Real World Coordinates)

Cartographic systems are included in the geospatial family of location referencing methods. It is framed according to the technology, standards and syntax of geospatial systems (SA, 2019).

GIS is a system that captures, stores, manipulates, analyzes, manages, and presents all types of geographical data. Traditionally, GIS, based on 2D maps, assigned 2D virtual references to real objects. The most common are longitude and latitude locations (Deng et al., 2016).

Geospatial referencing methods use a set of spatial coordinates by which location can be interpreted through many forms such as addresses or physical features. However, positioning is the most important locator for road asset management. Positioning consists of coordinates with reference to the Earth. It is supported by survey marks, Global Navigation Satellite Systems, geodetic modelling (coordinate transformations) and the geoid and bathymetric reference surfaces (West and Kenley, 2014).

5.1 Positioning location data

Geospatial data collection technologies including Total Stations (modern theodolites with built in Global Positioning Systems and laser ranging devices), full 3D static or mobile laser scanners, and photogrammetry cameras.

Traditional road asset management limits positioning to two dimensions. However, the traditional 2D location referencing method, is increasingly changing. The state road networks can now be surveyed with terrestrial laser scanners or mobile laser scanning systems to acquire 3D point clouds. These data are processed to extract the relevant location information, such as road center-lines, location of curbs, and other roadside furniture (West and Kenley, 2014).

5.2 Importance of topological location referencing

Searching and mapping are two key advantages of geospatial location reference systems. Most governments rely heavily on GIS applications, such as ESRI, for managing geographic data. Thus, local standards provide searching (proximity-based) and modelling abilities (SA, 2019).

GIS systems are able to utilise much more data than found in the road asset database. For example, datasets that provide population, terrain, or ground cover information. The typical application is therefore able to display a huge number of different types of features on a map providing searchable functionality (Niestroj et al., 2018).

Thus, features can be processed according to road user needs, as well as the needs of traditional road asset management systems. It can be argued that no modern road Location Referencing System will be able to avoid having a Geospatial location referencing method based on real world coordinates as part of their asset management system in the future.

6. Family Three: Geometric (Model Coordinates)

de Laat and van Berlo (2011) argue that there are two types of modelling worlds that are not able to integrate. The authors indicate this difference by suggesting that

> *"…the 'BIM people' and the 'GIS people' still seem to live in different [modelling] worlds. They use different technology, standards and syntax descriptions."*

Understanding this difference is important when considering the potential impact of BIM technology on location referencing methods and systems for road asset management.

Past efforts have paid little attention to either accuracy or discrepancy of location data due to the confusion between how systems use cartographic geometry. However, now that model geometry or modelling functionality resulting in 3D images continues to be developed, accuracy of location data presents a barrier to adoption of new technologies. At the same time, road transport agencies are being urged to move towards integration of digital engineering road design data in their asset management systems (Kenley and Harfield, 2018).

6.1 CityGML: linking geospatial and geometric location data

Currently in the GIS world, the cross-over from the BIM world for 3D representation uses City Geography Markup Language (CityGML). A number of scholars suggest that 3D GIS is an emerging technology Deng et al., 2016. For example, schemas such as KML, COLLADA and GML store 3D attributes of objects in GIS enhancing functionality.

CityGML has developed to be applicable for large areas and small regions and can represent the terrain and 3D objects in different levels of detail simultaneously integrating model geometry or cartographic geometry. Because of this functionality, both linear and coordinate location referencing datasets can be integrated into road asset management Location Referencing Systems.

However, the major barrier to adoption for road asset management is that CityCML points do not take into account the curvature of the earth, the continuing problem when using digital platforms (West and Kenley, 2014). All road construction must take into account the curvature of the earth, therefore any models, that do not, can only produce 'surplus to requirements' location data.

6.2 Designing road infrastructure

The family of Geometric reference systems are those based on geometric models of infrastructure. They are typically created and used during the design phase of road construction. At the simplest level, geometric systems draft 2D representations of the design using relative coordinates (relative to a fixed a known point). Such systems use different methods to calculate the positioning of lines. Importantly, they are generally based on mathematical formula to form vectors (Kenley and Harfield, 2018.

Geometric models of infrastructure include traditional 2D drafting of a project, through to 3D modelling, with the possibility of including modern BIM workflows. These are the tools and methods of 'BIM people' identified by de Laat and van Berlo (2011).

Their world-view is based on technology, standards and syntax related to object-based modelling (Steel et al., 2012). These types of models make intense use of 3D geometry embedded in Industry Foundation Classes (IFC) (Amann et al., 2015). IFC4 provides the rules for using the concepts of constructive solid geometry and boundary representation using Boolean operations to design geometric models of infrastructure, currently this means mainly vertical infrastructure.

However, it should be noted that the inclusion of older 2D and 3D modelling formats for infrastructure design means that Geometic location referencing methods are much more than BIM. At the most advanced level, complex and powerful integrated digital systems could build models of horizontal infrastructure, (Chen et al., 2015), however, continuing interoperability issues are slowing down that possibility (Kenley and Harfield, 2016; Steel et al., 2010).

6.3 Alignment, horizontal infrastructure, and modeling

Horizontal Infrastructure is the term that describes built environment and infrastructure assets created through string-based design such as networks. These typically are linear elements with alignment as the principle feature. The location breakdown structure creates continuous centre-lines.

However, BIM modelling has yet to develop effective methods of sending road alignment location information to road asset management systems. This is because an alignment is not composed of coordinate positions with straight lines between, as occurs in most geospatial location reference systems.

Road alignments consists of known points (geo-referenced) and polylines: lines made of multiple segments each being a line segment, a circular arc segment or a clothoidal arc segment (Amann et al., 2015). This specification does not force continuity between a point at the end of one segment and the start of the next (Kenley and Harfield, 2018). This is a common digital modelling dilemma, because of the need for a mathematical trade-off between positions calculated by curves and desired end-points.

An alignment may be seen as the direct equivalent to a Line Location except that dimensionality it is specific and is made of segments. However, some scholars claim that the horizontal alignment [only] is used for linear referencing, which was one of the principles for the development of the IFC Alignment schema (Amann et al., 2015).

6.4 Importance of geometric location referencing

Clearly geometric modelling using local coordinates is critical for the design of horizontal infrastructure. As a coordinate system and with local coordinates of all objects and alignments, this forms an extensive referencing system. Until IFC-Alignment forms the basis of equivalency to topological and geospatial reference systems, road asset management modelling data remains problematic. Thus, the necessity for having a framework with three distinctive families for Location Referencing Methods, as suggested in this paper.

7. Conclusions

The Topological, Geospatial and Geometric categories capture the necessity to consider past, present and future location data for road asset management systems. Both the functionality and problems of utilization of each of the families are described to encourage consideration of how each of the families can be adopted.

For many road asset management systems legacy linear/network location referencing methods can be considered mature. The location data from geospatial methods utilising GIS coordinates is becoming more common. However, the inclusion of location information captured in digital models is the most challenging for road asset management systems. Currently this category of location referring methods information integration is at a conceptual rather than an adoption stage for road asset management systems. Therefore, the continuing business drivers for digital information exchange benchmarks suggests the proposed location referencing methods framework must be the foundation of future adoption strategies.

Acknowledgements

The authors would like to acknowledge the support by the Australian Research Council, Grant No. LP116100524 and Austroads Grant No.ASP2112.

References

Amann A Borrmann T Chipman E Lebegue T, Liebich T and Scarponcini P (2015) IFC Alignment project, conceptual model, buildingSMART P6 Project Team Online: 15Apr19 http://www.buildingsmart- tech.org/downloads/ifc/ifc5-extension-projects/ifc-alignment/ifcalignment-conceptualmodel-fs

CEDR (2018) Contractor Report 2018-1 is an output from the CEDR Transnational Road Research Programme Call 2014: Asset Management and Maintenance. Online: 15Apr19 https://www.cedr.eu/download/Publications/2018/CEDR-Call-2014-Asset-Management-and-Maintenance_End-of-Programme-Report.pdf

CEN/TS16157 (2011) *Intelligent Transport Systems-DATEX II Data Exchange Specifications for Traffic Management and Information: Part 2: Location Referencing* (Online: European Committee for Standardization)

Chen K, Lu W, Peng Y, Rowlinson S and Huang GQ (2015) Bridging BIM and building: from a literature review to an integrated conceptual framework. *International Journal of Project. Management* **33** 1405-16

Choocharukul K, Sinha KC and Mannering FL (2002) User perceptions and engineering definitions of highway level of service: an exploratory statistical comparison *Transportation Research Part A-Policy* **38** 677-89

Committeri G, Galati G, Paradis A-L, Pizzamiglio L, Berthoz A and LeBihan D (2004) Reference frames for spatial cognition: different brain areas are involved in viewer-object and landmark centred judgements about object location. *Journal of Cognitive Neuroscience* **16** 1517-35

de Laat R and van Berlo L (2011) Integrating BIM & GIS: the development of CityGML GeoBIM extension. *Advances in 3D Geo-Information Sciences* (eds.) TH Kolbe, G König and C Nagel pp 211-25

Deng Y, Cheng JCP and Anumba C (2016) Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison. *Automation for Construction* **67** 1-21

Ebendt R and Touko Tcheumadjeu, L (2017) An approach to geometry-based dynamic location referencing. *European Transportation Research Review* **9** 38

HTC (2001) Task 2100: Principles of location Report for Transit New Zealand. Online: 15Apr19 http://www.lpcb.org/index.php/edocman-test/2001-new-zealand-location-referencing-requirements-in-transit/viewdocument

ISO17572 (2015) *Intelligent Transport Systems (ITS)-Location Referencing for Geographic Databases: Part 3: Dynamic Location References (Dynamic Profile)* (Online: International Organization for Standardization)

ISO19133 (2016) *Geographic Information: Location-Based Services: Tracking and Navigation* (Online: International Organization for Standardization)

ISO19148 (2012) *Geographic Based Information-Linear Referencing* (Online: International Organization for Standardization)

Kazemi S and Forghani A (2016) Knowledge-based generalisation of road networks. *International Journal of Geoinformation* **12** 1-13

Kenley R and Harfield T (2018) Scoping study for a location referencing model to support the BIM environment. *Research Report AP-R568-18* (Sydney: Austroads)

Kenley R and Harfield T (2016) Challenging the role of location in Industry Foundation Classes. In the *Proceedings of CIB W78 Conference 2016*, 31 Oct - 2 Nov 2016, Brisbane. Online: 15Apr19 http://hdl.handle.net/1959.3/433406

Lobben A (2004) Tasks, strategies, and cognitive processes associated with navigational map reading: a review perspective. *Professional Geographer* **56** 270-81

Niestroj MG, McMeekin DA and Helmholz P (2018) Overview of standards towards road asset information exchange. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* **XLII-4**

NCHRP (2001) Report 460-guidelines for the implementation of multimodal transportation location referencing systems. *National Cooperative Highway Research Program* Online: 15Apr19 http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_460.pdf.

Ries T (2000) Integrating traffic management data via an enterprise LRS Online: 15Apr19 https://ntl.bts.gov/lib/10000/10900/10985/027ppr.pdf

Roess RP and Prassas ES (2014) *The Highway Capacity Manual: A Conceptual and Research History* (Switzerland: Springer International Publishing)

SA(2019) South Australia Spatial Services Contractor standards GIS Standard Specifications – GIS-CT001 Online: 15Apr19 https://www.dpti.sa.gov.au/__data/assets/pdf_file/0006/393756/GIS-CT001_Geospatial_Services_Specifications.pdf

Oracle Docs (2019) Spatial Concepts: A geospatial database overview Online: 15Apr 19 https://docs.oracle.com/cd/B28359_01/appdev.111/b28400/sdo_intro.htm#SPATL010

Steel J, Drogemuller R and Toth B (2012) Model interoperability in Building Information Modelling. *Software and Systems Modelling* **11** 99-109

West, GAW and Kenley R (2014) Geographic data and systems in project planning, Position Paper 3 *SBEnrc Project 2.21 New Project Management Models for Productivity Improvement in Infrastructure. Online:* 15Apr19 http//hdl.handle.net/1959.3/420032

Security Model Collaborative Building Design

Kaznah Alshammari[1, *], Prof. Haijiang Li[1] and Prof. Alan Kwan[1]
[1]Cardiff University
[*]email: alshammarik1@cardiff.ac.uk

Abstract

This research concerns the topic of Building Information Modelling (BIM), data governance and security frameworks directed towards finding an appropriate method to security model a collaborative building design. This is concerned with knowledge of the structure and model of information that is utilised in the collaborative building design, the security threats that face the structure and model of information and concerning information security to achieve the stated goal.

BIM implementation has benefits associated with the BIM process. These benefits include the flexibility of workflow and that performance in collaboration can be facilitated to model data integration. Team members can work uninterrupted on the same model. However, there are certain steps that can be taken to control the model and manage it without inconsistencies arising. Some of these steps include assigning users to a workstation so that others are prevented from making changes to features at the same time. In addition, when a modification is made, a copy of the system must be synchronised with the local copy in order to achieve intergradation with the central model of BIM. The collaboration problem was not complex prior to BIM because the participants would simply work on different sheets. BIM effectively processes the inefficiencies and inaccuracies of the traditional methods at a cost of reduced flexibility and an increase in collaboration complexity. Problems can arise when an application has a centralised model of approach because most files are contained in a single file.

Having understood the information model and related security threats, the model proposed to secure the BIM for a collaborative building design is developed to prioritise the security of all information exchanged between the involved parties. The security model that is proposed addresses security concerns: protection of building information from access by unauthorised individuals and the creation of information in the BIM through unauthorised access.

The security model allows for the arrangement of data according to measures put in place according to the classification of information in the BIM. The model also records the activities of users to enable any breach to be traced to a particular user. The model uses these user activity records and defines patterns and best practices that reduce the probability of information compromise in the BIM. Many security models only store information and place little emphasis on protection or the access that users are granted to this information.

Keywords: BIM, collaborative building design, information security, access controls and multi-layered security.

1. Introduction

In the modern world, the construction industry creates amazing architecture and seemingly impossible building designs such as the tallest building in the world which is currently the Burj Khalifa in the United Arab Emirates. Such architecture requires considerable input and effort, whereas more is expected from the well-informed consumer. Such an environment in the construction industry calls for the implementation of a technology and information basis. All of the stakeholders involved in projects are to keep abreast of the latest information and direction of the projects. It requires competent coordination and collaboration in a concept that has come to be defined as collaborative building designing (Chen et al., 2005). Such a collaborative environment demonstrates an increased security threat regarding the information exchanged and accessed by the numerous stakeholders directly involved. Information is very valuable and is always at risk on account of the modern threats to the security of information.

Information security challenges have been a problem for collaborative organisations for long as information models have existed. Collaborative environments in the construction industry have faced growing cases of information security breaches that have been known to bring projects to a complete standstill. Management has struggled to tackle information breaches, loss and information system damage. Few have been able to recover from the problem and resume normal business operations or carry out a complete turnaround to install and integrate new, safer information models and provide better services to their consumers (Merkow & Breithaupt, 2014).

The increase in cases of information breaches are attributed to a lack of accurate understanding about information models by management that initially result in the establishment of poor information models that are highly susceptible to attacks, theft, hacking, and unintentional mistakes by internal personnel. The effects of misunderstood information model management among management boards include the failure of organisations to stay up-to-date with the respective information model and constantly manage their systems to ensure they are safe from attack, theft and error that may lead to problems (Ifinedo, 2011).

The aim of this paper is to create an appropriate security model for a collaborative building design in the construction industry. The security model that is proposed addresses security concerns relating to the protection of building information and also information in the BIM from access by unauthorised individuals. This security model depends on a three-layer approach to deal with access-based security for building management information. The security model takes into account the arrangement of data as per measures set up for the classification of information in the BIM. The model likewise records the activities of users to enable any breach to be traced to a specific user. The model uses these user activity records and characterises patterns and best practices that reduce the risk of information being compromised in the BIM. Therefore, the proposed model has the features required to realise successful security for building information models.

The paper is organised as follows: in Section 2, related works define the building information model, collaborative building design, and information system security; Section 3 sets out the methodology for the proposed security model collaborative building design, and security model development; Section 4 presents the results and provides a discussion; while Section 5 concludes.

2. Related work

2.1 Building information model

Architecture, engineering and construction (AEC) create and design three dimensions (3D) modelling using BIM software which is a platform that makes the communication of project ideas and design easier. It also provides tools for buildings and infrastructure that contain big data and allows the exchange of BIM data between BIM users (Autodesk, 2003).

Autodesk "Revit" is a type of BIM software intended for architecture, structure and mechanical, electrical, and plumbing (MEP). It is a strong development platform that enables architects and engineers to plan and design a building and its elements in 3D. It also enables comments to be added to the model with two dimensions (2D) drafting components and access building data from the model database. Revit is 3D plus time schedule (4D BIM) which as a tool is used to plan and design all parts of a building project from construction to demolition. Additionally, the Revit interface supports various methodologies for utilising the Revit. Therefore, it provides a high level of elasticity for architects and designers. Autodesk "Revit" does not run on all operating systems, e.g. the Apple Macintosh operating system (OSX). Because the file size is expandable, Autodesk "Revit" needs to fasten to a central processing unit (CPU). Autodesk "Revit" is an import and export tool for common types of files containing 3D models, 2D drawings and other types of file ("Which BIM software is better? ArchiCAD vs Revit? - Cadonia", 2019).

Autodesk "Revit” contains several tools offering specific functions used by Revit users (engineers and architectures) to create and design buildings (Lee & Wu, 2005). The tools in Autodesk "Revit” are not just to create and design, they also serve the BIM group by exchanging BIM data and are connected between them. Autodesk "Revit” permits a link with a BIM database by using an existing plugin called ‘Revit DB link’ (Autodesk, 2003).

BIM data in database can be stored through the Revit interface using the existing plugin with Revit called ‘Export.’ Additionally, Autodesk "Revit” deals with certain software and folders (e.g. Microsoft SQL server management and Visual studio.NET software; Integration service script component; custom office template) to add new features by using the existing plugin with Revit called ‘File Data Source.’

The BIM method is built for design, construction and project management. It also stores and retrieves big data in the BIM database. Therefore, project teams have a database structure to link it with BIM project data. BIM modelling utilises existing commercial software such as Revit (Autodesk), Constructor (Microsoft) and Microstation (Bentley). Each piece of software connects with a unique BIM database to store and retrieve big data for the BIM project. Autodesk “Revit” uses an existing plugin with Revit that relates types of files to the BIM database (Cha & Lee, 2015).

2.2 Collaborative Building Design

Modern technology has brought about numerous changes in the construction industry and the industry is no longer merely physical but rather data-based. The industry has taken a turn towards the inclusive involvement of all stakeholders in a development project or a real estate project coming up with a certain facility. The modern construction industry requires a constant transaction of information and data. This data is key to ensuring that all members of a project team understand the direction the project is taking. To bring all this information to a common access and effectively engage in BIM, there is a need for the effective collaboration and coordination of data, as shown in Figure 1 (Chen et al., 2005). All of this data is very important and needs to be secured. This calls for the development of effective security models for collaborative building design.

When implementing the BIM, there are benefits associated with this process but that does not mean that they are necessarily achieved. Some of the benefits include flexible workflow and even the performance in collaboration can be reduced to model data integration. Team members can work uninterrupted on the same model. However, there are certain steps that can be taken in order to control the system and manage it without any inconsistencies. These steps include assigning users a workstation so that other users can’t make changes to features at the same time. Simultaneously, when changes are made, it is necessary to update or synchronise the system using a local copy to ensure a connection with the central BIM model.

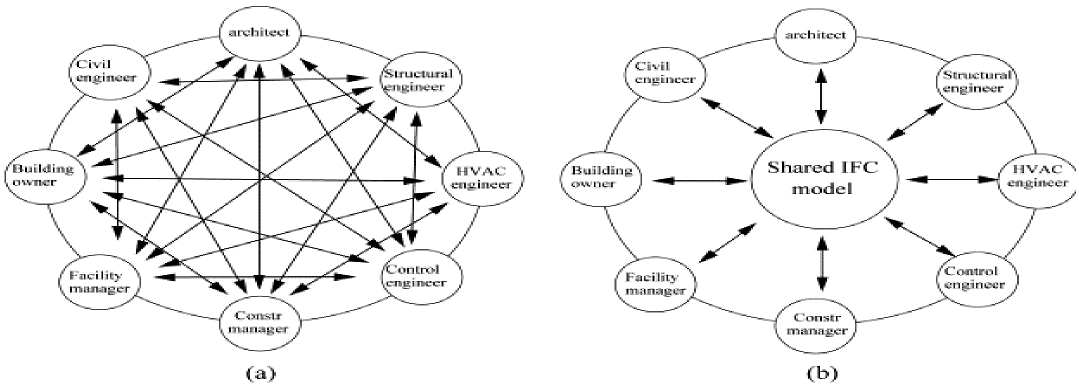


Figure 1 Collaborative building design information flow (Chen et al., 2005).

Most BIM has flexibility limitations which affects the collaborative style in the organisation. As a result, the software is affected by the trade-off between workflow flexibility and the barriers set in collaborative performance. An increase in data integration is met with reductions in both performance and workflow flexibility. It is necessary to actively manage the changes being made by the various members of a project team when they are working concurrently because failure to do so will result in conflict (Teamwork & Ipd, 2009).

In this case, the architects and engineers need to work together in order to accomplish the best outcome and utilisation of a building. As architects become increasingly aware, they specialise and projects become more complex. The design disciplines when working on the same building remain with workers using their own sets of tools and practices (Sacks, Koskela, Dave, & Owen, 2010). This makes the common issues experienced in communication and coordination in a normal office set up no different in this area. In construction, collaboration can be understood as the internal and external processes that occur when the users who edit or modify a model within or outside the organisation do so simultaneously. Sacks, Koskela, Dave, & Owen, (2010) noted that whereas it is possible to lock away internal objects to prevent irregularities when they are edited to create additional versions, when utilising the external method, it is only the representations that are shared and cannot be edited. This mitigates the problem but has the effect of making it necessary for the various disciplines to each amend their specific objects.

The collaboration problem is not complex prior to BIM because the participants would simply work on different sheets. BIM effectively handles the problematic inefficiencies and inaccuracies of the traditional methods at a cost of less flexibility and an increase in collaboration complexity. Therefore, in this case the collaboration problem is more complex following the introduction of BIM because the multidisciplinary team members have to work in a synchronised model. The problem intensifies when an application has a centralised model of approach because most of the files are contained in one file.

2.3 Information system security

Information security is a collection of practices that prevent unauthorised access, disclosure, use and modification. Information security refers to the security of the components of the information model (Whitman & Mattord, 2017). These include hardware security, software security and personal security. Information security needs can be expressed in four main categories. These ideas ensure that information security is maximised by preserving confidentiality, integrity, availability, and configuration in an information system (Kim & Solomon, 2018).

Information confidentiality: determining who has access to information so as to ensure that unauthorised persons cannot gain access to sensitive or classified information.

Information integrity: ensuring compliance with procedures concerning how information is modified and deleted.

Information system availability: ensuring that access is only granted to authorised persons and that they use the information in accordance with the stated policies.

System configuration: ensuring that an information system's configuration settings can only be changed by those who are authorised to do so in accordance with the stated system modification guidelines.

3. Methodology

3.1 Proposed Security Model Collaborative Building Design

Upon understanding the information system security threats (including viruses, spam and internal theft of information), the model that is proposed to secure the BIM for a collaborative building design is developed to prioritise the security of all information exchanged between the parties involved using secure communication, classification and authorisation of access and prioritising the security of the host cloud. The model proposed is a dedicated system for the storage of building information systems. This model was not implemented to store and secure personally identifiable information; rather, building information exchanged in a collaborative building design such as agreements, intellectual property, financial information relating to projects and contracts.

The security model that is proposed addresses two significant security concerns:

- Protection of the building information from access by unauthorised individuals and any creation of information in the BIM by the unauthorised persons.
- The security model also ensures that there is information available to authorise access within a hosted cloud environment. It provides prompts and guides to successfully complete the task at hand and uses the authority level of the user to access information instead of leaving the user with the task of going through stored archives to obtain the information required for the task at hand.

Figure 2 shows a multi-layered approach to ensure the security of the collaborative building design information to address these two concerns.

3.1.1 Layers of the proposed security model collaborative building design

First layer of the security model: The building information context and the classification of the building information data that support information security.

Upon the data interchanged in the collaborative building design being classified, the building information will be stored in the security system based on sensitivity and criticality. This information is a confidential building information system and strictly not individual sensitive data.

The proposed security model classifies the information in the BIM (see Table 1). The security model then uses this classification to make authorisation levels based on the needs of the collaborative building environment stakeholders. The authorisation levels are customised to each collaborative environment from the lowest to the highest in hierarchy. The entities in the authorisation level will require authority to access information above their level.

The classification is as follows:

Pubic information: This information is available to the general public such as occupational opportunities in the project. Compromises information that has no impact on the security of the BIM.

Employee confidential: This includes standards, guidelines, procedures and processes utilised in the building information. Compromises information that could cause harm to the organisation including the exposure of competitive advantages.

Non-disclosure agreement (NDA) confidential information: This includes documents that are only accessed by stakeholders with non-disclosure, including agreements and contracts relating to collaborative building design. Compromise of such information would inflict significant damage to collaborative building design.

Insider restricted information: Such information includes intellectual property, project plans and financial data. This data is only accessible by people who have signed an agreement never to disclose any information that is top secret for the BIM.

Private information: Personally, identifiable information such as financial records that are only accessible by the owner of the information. Any compromise could lead to a loss of credibility for a project.

Table 1 Classification of the information in the BIM

Classification	Colour Code (Model Diagram)	Impact of compromise
Public		None
Employee Confidential		Limited
NDA Confidential		Significant
Insider Restricted		Significant
Private		Serious

Second layer of the security model: Controls built into the system that are customised to the collaborative building design environment.

These security controls are developed to fit the specific requirements of different collaborative building designs and secure the building information interchanged by stakeholders. These user requirements for collaborative building designs include user identification, user specifications for the security model, user designs and interfaces that will be integrated into the security model.

The controls include:

Access controls: The access controls secure the BIM. Access is only allowed to assigned users given permission to access and execute the function of the system including the creation records and retrieval of data. Any compromised access triggers will result in account lockout based on the specified rules.

Version control: This control keeps a tab on the edits made to the BIM. These changes are traced back to an individual user and, therefore, provide accountability. The security model logs the activities of each user and the information they input into the BIM. The changes are tracked to the specific users. The information that existed (prior version of the information) is stored and archived. The prior version of the edited data is archived in the security system for retrieval by those with prioritised access.

Audited logging: Audit trails are created by the security system for all activities by an assigned individual with authorised access. This control also establishes accountability and monitors the performance of stakeholders in the collaborative building design environment. The application of audited logging in the security model is to maintain a record of each activity performed by the users and, therefore, trace back any breach of information to the user ID and manage the threat.

Third layer of the security model: practical security.

Development cycle of security: The system allows for the development of customised security models from configuration to final implementation. This ensures that the requirement of different collaborative environments is met.

Depth of defence: Multi-layered security will be utilised in the proposed model within collaborative environments, as elaborated in Figure 2. There will be multi-tenanted network segments in between the internet and the system and all data for the BIM entailing public to private information as specific to the classification of information in the security model.

Patch management: New threats to information security are introduced into the construction industry each day. This calls for the implementation of security measures to sufficiently protect building information in collaborative environments. Patch management will be the responsibility of the providers of the security model to maintain the system and continually update the security measures. This function will test and install multiple code changes to continually secure the BIM against new security threats.

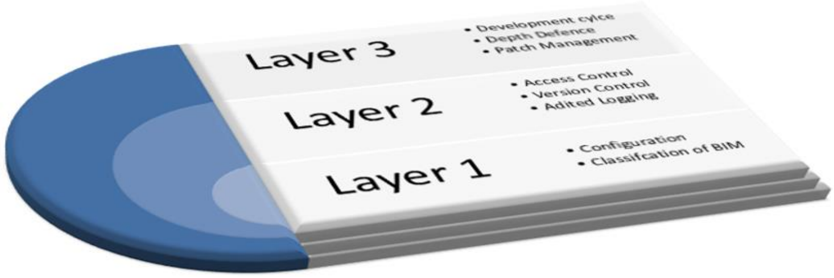


Figure 2: Proposed security model Collaborative building design

3.2 Security model development

The security model proposed will utilise C# which is a very powerful programming language that has been put to various uses in modern technology. The security model proposed will effectively use a three layer design to carry out access clearance based security for building management information in a Structured Query Language (SQL) server database system. The security model will comprise the following layers: User interface layer (Layer 1), Business logic layer (Layer 2) and Database access layer (Layer 3).

The multi-layered approach helps to ensure that change management is able to be implemented. Changing content in the business logic layer, for example after some period of use, will not affect the database access layer or the user interface layer. C# will be utilised to develop the three layers of the security model, whereas further security shall be provided by the Advanced Encryption Standard for sensitive data.

User interface layer: The user interface layer will be simple to use and graphical to help users. This layer will contain the web forms for web-based applications.

Business logic layer: This layer will essentially contain the specific areas or rather part of the system that will create the logical or business rules for access to, and creation and modification of the data. It will allow these functions based on user clearance and access controls in the system. The business logic layer will have functions such as access control, version control and audited login. C# will create parameters that will only allow the user to process from the business logic layer (layer 2) to the data access layer (layer 3) given that the SQL query of the clearance and the stored procedure of access remains true. The version control will allow the creation and modification of data in the SQL server database (DB) given that clearance and the stored procedure of access remains true. The audited login will keep records for user access into the data access layer through the business logic layer to track user activity in the security model.

Data Access Layer: The database that the system will be utilising is the SQL server. Data access prevents authorisation by managers, owners and the board depending on their clearance level.

4. Results and discussion

BIM Design collaboration is new phenomenon to the AEC industry. There is not a secure model for BIM that facilitates a collaborative approach to designing buildings while ensuring the security of the information exchanged by those involved in the process when discussing matters such as intellectual property, agreements, contracts and financial information. Consequently, this research proposes a security model based on a three-layer approach to deliver access clearance-based security for building management information.

This research has delivered a security model collaborative building design of BIM that can improve the information security of BIM for stakeholders. It integrates a BIM collaborative building design and information security to help secure the design process of BIM based on the amalgamation of control access and BIM data. It enables communication between stakeholders with a high security model and team members can work uninterrupted on the same model.

The security model collaborative building design that is proposed in this paper to manage BIM information in collaborative building designs involves version control, access control and audited logging. Adopting such an approach ensures that only authorised users are able to access and perform the function. Any previous versions of the data are stored within the security system so that they can be retrieved if needed at a later date with the changes made by each individual being logged.

The security model also comprises the user interface layer, business logic layer and the database access layer. It is this multi-layered approach that enables change management to be delivered. For instance, making changes to the business logic layer's content has no effect on either the user interface layer or the database access layer. All three layers of the security model will be developed using C#, with additional security to protect particularly sensitive data being delivered by the Advanced Encryption Standard (AES).

The security model collaboration building design on BIM can be validated by experts in terms of the accuracy and completeness of the data and the effectiveness of the security model.

5. Conclusion

Security is a very important aspect in constantly changing collaborative building designs with numerous stakeholders required to access and generate information for useful outcomes. This research implements a holistic approach that makes allowance for the security threats facing collaborative BIM to develop a security model that reflects the security risks that challenge collaborative environment information in the construction industry. The proposed model has the features required to enable effective security for BIM.

Acknowledgements

The author acknowledges the Northern Border University, Saudi Arabia for the assistance offered. However, the opinions and statements presented in this paper are purely those of the author and are not necessarily endorsed by the University.

References

Autodesk. (2003). Building Information Modeling for Sustainable Design. Autodesk White Paper, 1–13.

Which BIM software is better? ArchiCAD vs Revit? - Cadonia. (2019). Retrieved from http://cadonia.com.au/which-bim-software-is-better-archicad-or-revit.

Cha, H. S., & Lee, D. G. (2015). A case study of time/cost analysis for aged-housing renovation using a pre-made BIM database structure. KSCE Journal of Civil Engineering, 19(4), 841–852. https://doi.org/10.1007/s12205-013-0617-1.

Chen, P., Cui, L., Wan, C., Yang, Q., Kiong, S., & Tiong, R. L. K. (2005). Implementation of IFC-based web server for collaborative building design between architects and structural engineers, 14, 115–128. https://doi.org/10.1016/j.autcon.2004.08.013.

Kim, D., & Solomon, M. (2018). Fundamentals of information systems security (3rd ed., Chapter 4).

Ifinedo, P. (2011). Understanding information systems security policy compliance : An integration of the theory of planned behavior and the protection motivation theory. Computers & Security, 31(1), 83–95. https://doi.org/10.1016/j.cose.2011.10.007.

Lee, A., & Wu, S. (2005). The utilisation of Building Information Models in modelling: A study of data interfacing and adoption barriers, 10(February), 85–110.

Merkow, M. S., & Breithaupt, J. (2014). Information Security: Principles and Practices (2nd ed., Chapter 2).

Sacks, R., Koskela, L., Dave, B. A., & Owen, R. (2010). Interaction of Lean and Building Information Modeling in Construction, 136(September), 968–980.

Teamwork, G., & Ipd, B. I. M. (2009). NEXT-GEN BIM, (25).

Whitman, M. E., & Mattord, H. (2017). Principles of Information Security, (January 2005).

A Multi-Level Model of Collaboration – Lessons Learnt from Social Scientific Interpretive Research

S. F. Sujan[1,*], S. W. Jones[1], A. Mannis[1], Pedro Mêda[2] , Eilif Hjelseth[3] , A. Kiviniemi[4] and J. M. Wheatcroft[5]

[1]School of Engineering, University of Liverpool, United Kingdom
[2]CONSTRUCT-Gequaltec, Construction Institute, Faculty of Engineering, Porto University, Portugal
[3]Department of Civil Engineering, Norwegian University of Science and Technology, Norway
[4]School of Architecture, University of Liverpool, United Kingdom
[5]School of Natural and Social Sciences, University of Gloucestershire, United Kingdom
[*]email: S.F.Sujan@liverpool.ac.uk

Abstract

Many scholars claim that the impact of systemic innovation e.g. Building Information Modelling (BIM) is not as expected. Understanding the root causes, evaluating the implications and developing solutions should therefore constitute the main aspects of reflection. The literature contains numerous papers focusing on the adversarial and transient nature of the construction industry. However, authors feel that they fail to identify the root cause of the challenges. These affect the cohesion and the productivity of the industry with reflections on the efficiency and performance of construction projects. Holistic understanding is needed as changes need to reflect reality to bring positive results.

The research illuminated key elements, via a qualitative study which comprised of focus group discussions with multiple firms operating in design and construction in Norway, and one-to-one interviews with a project management firm in Finland. The focus groups and interviews were conducted around a central theme of collaboration in an unstructured manner to ensure meaningful data was collected which reflected reality. Thematic analysis was used to process the data, and the model was developed based on the most frequent themes. In addition, the experience of the authors from projects in multiple localities has been called upon to evaluate the results.

The purpose of this paper is to present a holistic model to increase understanding of the origin of challenges in collaboration at the project level in the AEC (Architectural-Engineering-Construction) industry. The aim of this model is to interpret the origins of the current reality of collaboration and its implications on future processes where more innovations may well be introduced.

Empirical findings suggest multiple origins of challenges systemically affect collaboration and digitalisation at the project level. The addition of Human Psychology and Culture (HP&C) as a foundation was used to reflect the natural characteristics of people emergent in the qualitative data. Overall, the findings provide evidence for systemic challenges related to interdependencies between the HP&C and project level, transactional, intra-organisational and industrial factors.

Keywords: Collaboration, Human Factor, Social Science, Psychology, Construction management

1. Introduction

Despite advanced technological development in the Architectural-Engineering-Construction (AEC) industry, exemplified by use of BIM, efficiency and productivity improvements have been negligible at a sector level, although with notable exceptions at a project level. This paper presents a multi-level model based on qualitative data centered on project level collaboration; the unstructured format brings multiple factors that interact reciprocatively. In this paper, the root of challenges and difficulties in the industry are argued to be heavily dependent on human constraints as a result of the decision-making process of people. Psychological theory regarding decision-making and cognitive/motivational biases has been applied to client-centered decisions to show the role of the rooted human nature (Sujan et al., 2019). These biases are said to be as a result of different types of beliefs (normative, behavioral or control) forming the foundation of decision making (Ajzen, 1985).

The study and its prequels (Sujan et al., 2019, 2018) go against domain trends; AEC literature is highly technical in nature (Hjelseth, 2017; Sousa & Mêda, 2012) and positivist in nature (Barrett, 2018), as such, awareness of hidden aspects are required for further understanding in practice and research. Sujan et al., (2018) presents the methodology used to study collaboration holistically and presents some empirical lessons. Further, Sujan et al., (2019) uses psychological theory and empirical data to show the dependency of client-involved decision-making on beliefs; the study formed the basis of using the multi-level model that is presented here. The paper thus aims to show the rooted nature of collaboration factors in human capability. Collaboration factors were extracted from qualitative data and put in a Holistic Model for Collaboration in the AEC industry (HMC-AEC) depending on its definition and interaction with other factors.

Therefore, the objectives of this paper are:

- To determine the importance of human factors
- To compare AEC models with similar industries' models
- To present a multi-level model that suits the interdependencies of factors with regards to collaborative working
- To assess current models used in the AEC industry and compare the HMC-AEC structure

2. Review of Literature

2.1 The Human Factor in Other Industries

The AEC industry is described as a Project Based Inter-Organisational Network (PBION) similar to the film, healthcare and defense industries (Taylor, 2005). Therefore, value can be driven regarding the human factor. The biopsychosocial approach was presented in by Engel in 1977, to show the reductionist's over-simplification effect in the biomedical model where physical origins are assumed to be causes of diseases. A patient's illness has been defined by western medicine in a reductionist approach from the 16th and 17th centuries with the idea that mind and body are separate phenomena, still a majority view in today's healthcare practice delegated by the biomedical model (Wade & Halligan, 2017). As Engel (1977) explained, with the biopsychosocial approach, there is a need to consider both the social/psychological and physical dimensions of illness and the patient. Although this simplification did have considerable success in the diagnosis and treatment of life-threatening diseases, well recognized illnesses with no physical origin are not accounted for (e.g., 'neurasthenia'). Other scholars supported this view that (Kleinman, Eisenberg, & Good, 2006) in simplifying the way knowledge is created, all possibilities of intervention or innovation are not captured (Kleinman et al., 2006).

The UK government released Human Factors Integration (HFI) regulation in the defense industry which seeks to provide a lens to the industry from a human capability standpoint and not discerning the more technical policies, made to supplement them (Ministry of Defence, 2015). The regulation does not intend to give a technical and high level of detail; however, it provides a holistic view of the process by clarification of solutions which otherwise would have multiple methods. This is so that people can align their mental processes giving common ground for normative beliefs to develop as well as uniting the risk perception. Many risks at the project level are not independent nor systemic in nature; they have influence on multiple teams.

2.2 Integrated Design & Delivery Solutions (IDDS)

The IDDS model was developed as a grounded concept involving consultation with several hundred people around the world. Three parts of the model included collaborating people, integrated processes and interoperable technologies represented in a single level overlapping with IDDS in the center (Owen, Amor, Dickinson, Prins, & Kiviniemi, 2013). IDDS has had a significant impact in helping researchers and practitioners understand the complexity of the reality of collaborating using integrated processes and interoperable technologies. Additionally, its purpose is to develop new approaches to integrated design and to engender debate about the development of industry. IDDS' definition of collaborating people, was utilized as a point of departure.

3. Methodology

The Cynefin framework can be used to describe the value gained from an unstructured approach to qualitative data gathering (McLeod & Childs, 2013). The unstructured approach to qualitative data is utilized to gain an in-depth understanding of phenomena by understanding human experiences (Wildemuth, 2016, pp. 239–247). The authors wanted to understand the complexity of collaboration so that a model could help raise awareness of the hidden factors and interdependencies of factors. The aim was therefore to study complex phenomena and represent it in an ordered manner. From the Cynefin framework, complex aspects are investigated by a process of sense-making which involves exploration of concepts and dependency (McLeod & Childs, 2013). Similarly, in the development of the model, open approaches to data gathering gave the researcher a view of reality from the experiences and opinions of participants. Sense-making happened at two levels:

1. During the interview/focus group – the unstructured approach to qualitative data gathering requires the researcher to understand responses and respond dynamically with questions regarding further explanation or probes to bring out underlying aspects regarding phenomena discussed.
2. During the analysis – this involved being thorough with the data via thematic analysis and understanding the bigger picture by generalizing between types of participants and their opinions. Thematic maps of factor interactions were made to gain a holistic understanding of the complexity.

Table 1: Study Overview (Sujan et al., 2019)

		Study	
Location		**Study 1: Finland**	**Study 2: Norway**
Approach		End to End, One Firm Perspective	End to End perspective Multiple Firms
Duration		5 Days	5 Days
Method	**Focus Groups**	Nil	5 (14 participants)
	Individual Interviews	18	Nil
Analysis	**Qualitative**	Thematic Analysis	
Participant Classification		End to End Project Management (Design and Production Managers)	2 Contractors, 1 Project Management, 1 Public Client, 1 Consultant, 1 Industry Organisation

The aim was to use collaboration as a central theme to let the responses evolve based on reality. The main challenge with this approach was the intense and time-consuming analysis as different patterns and structures of data arise from one session to another. This brings width and depth which enables rich data – the analytical approach lends itself to this data and is therefore not a limitation but a strength.

To add a further layer of analysis, semi-structured interviews were also conducted with experts from the UK AEC industry; the questions evolved as a result of analysis of Study 1 and 2 data and the developed model. The approach was to enable a level of validation to verify the analytical perspective of the researcher. The structure of the model was verified with all experts providing examples of the rooted nature of human psychology and culture in daily project practice.

4. A Multi-Level Representation of Inter-organisational Collaboration

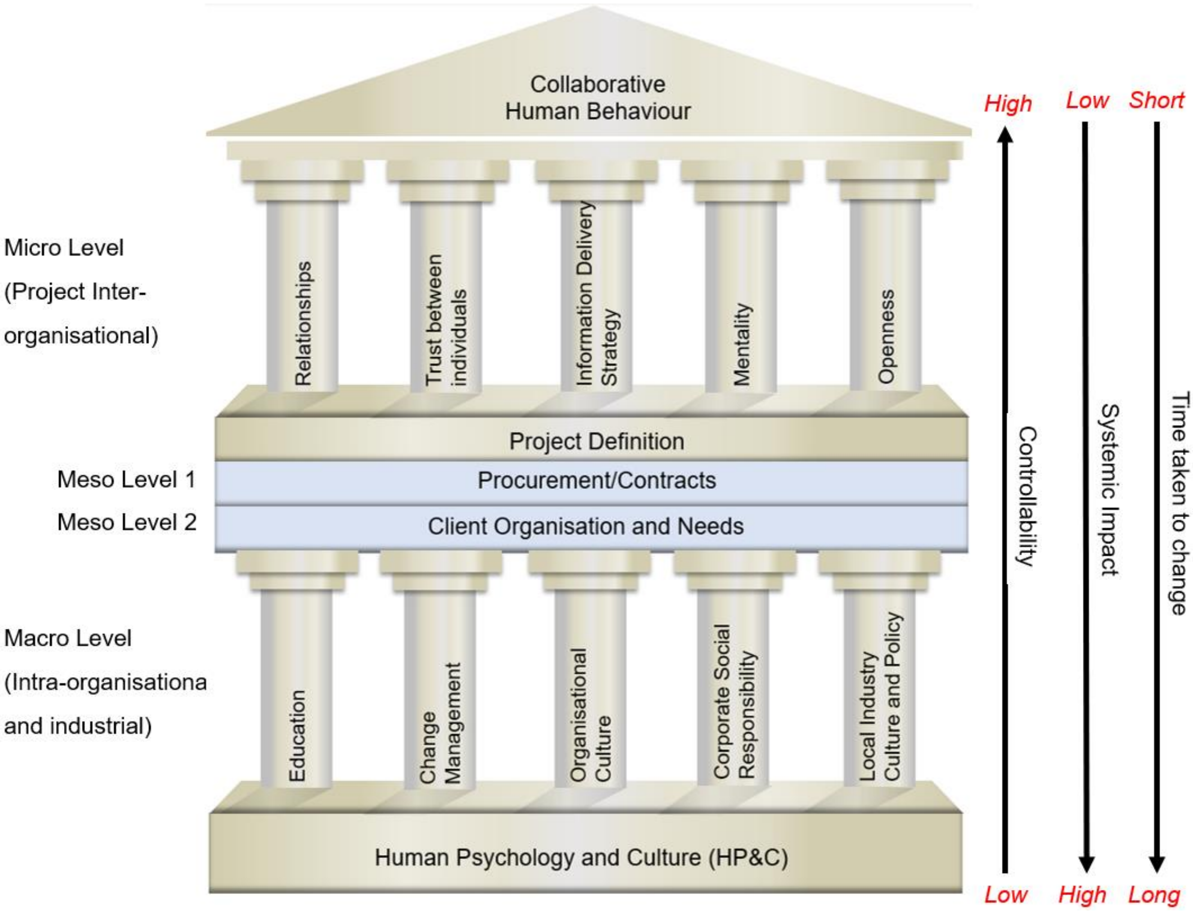


Figure 1: Overview of the Holistic Model for Collaboration in the AEC industry (HMC-AEC)

Figure 1 shows an overview of the levels of the Holistic Model for Collaboration in the AECOO-industry (HMC-AEC). The foundation for HMC-AEC is based on the Ph.D. thesis by Sujan (2019). The Micro, Meso and Macro levels are consistently defined as in Van Notten's external analysis model (Van Notten, Rotmans, Van Asselt, & Rothman, 2003). The Micro level represents the factors that are apparent at the inter-organisational project level. The Meso levels are respective of the transactional factors, which in this context are split between the client and the contracts. As represented in the figure, the client aspects are below the contractual aspects; empirical data showed that the contractual aspects depended on the nature of the client organisation. The way the contract is perceived or used in a project depends on client organisational culture and styles of dealing with project participants. The macro level represents factors found within organisations independently or at the industrial level which delegate normative practice. The novelty in structure is highlighted in the level below the Macro called Human Psychology and Culture (HP&C). The factors found in this level are foundational to all the other levels and have a complex influence on each factor either directly or hierarchically. If an empirical factor emerged in all the other levels, it was repositioned in the HP&C level. For example, trust was initially at the Micro level, however, after expert interviews, it was found that it was present in all the levels and therefore was repositioned to the foundation.

4.1 Trust as an Example of Multi Level Interdependency

Figure 2 shows the categorisation of factors found from qualitative data and arranged in the Holistic Model for Collaboration in the AEC industry (HMC-AEC). The HP&C level should be perceived as foundational to all levels as it can be related to every other level in the model. This section uses trust to exemplify the nature of multi-level interactions between factors:

Micro – Meso 1: The link between individual trust and the Meso level can be viewed around financial incentives of a project; if there is friction between teams about win and loss this affects trust between them.

Meso 1 – HP&C: The way teams are selected is predominantly price based and transient in nature. Evidence suggests that trust development is not possible with all teams even if the social climate is positive. This means that there are characteristic traits of a team and individuals that require studying in the selection process.

Micro – Meso 2: The client is the main decision maker in the project. The relationship of teams with the client is found to be vital in having a positive social climate in the project; with a good relationship, people tend to exert more freedom to be open which means that there is more efficient communication between teams and the client.

Micro – Macro: Trust between organisations was related by experts to business ethical practice in the industry. From empirical evidence it was found that it is normal practice to provide information at tender stage (to win the project) that differs to reality after award.

Micro – HP&C: Trust between individuals was linked to the individual's attitude to trust/mistrust which is a result of multiple factors both from the individual and culture the individual works in. For example, personality is the individual aspect which directly affects the way the said individual trusts, a trustful personality will begin relationships at the point of trust. External aspects include cultural expectations of behaviour and process which became evident when participants described interactions with firms that were not from the local industry. These expectations are developed from years of normative practice and socio-cultural aspects relating to business practice.

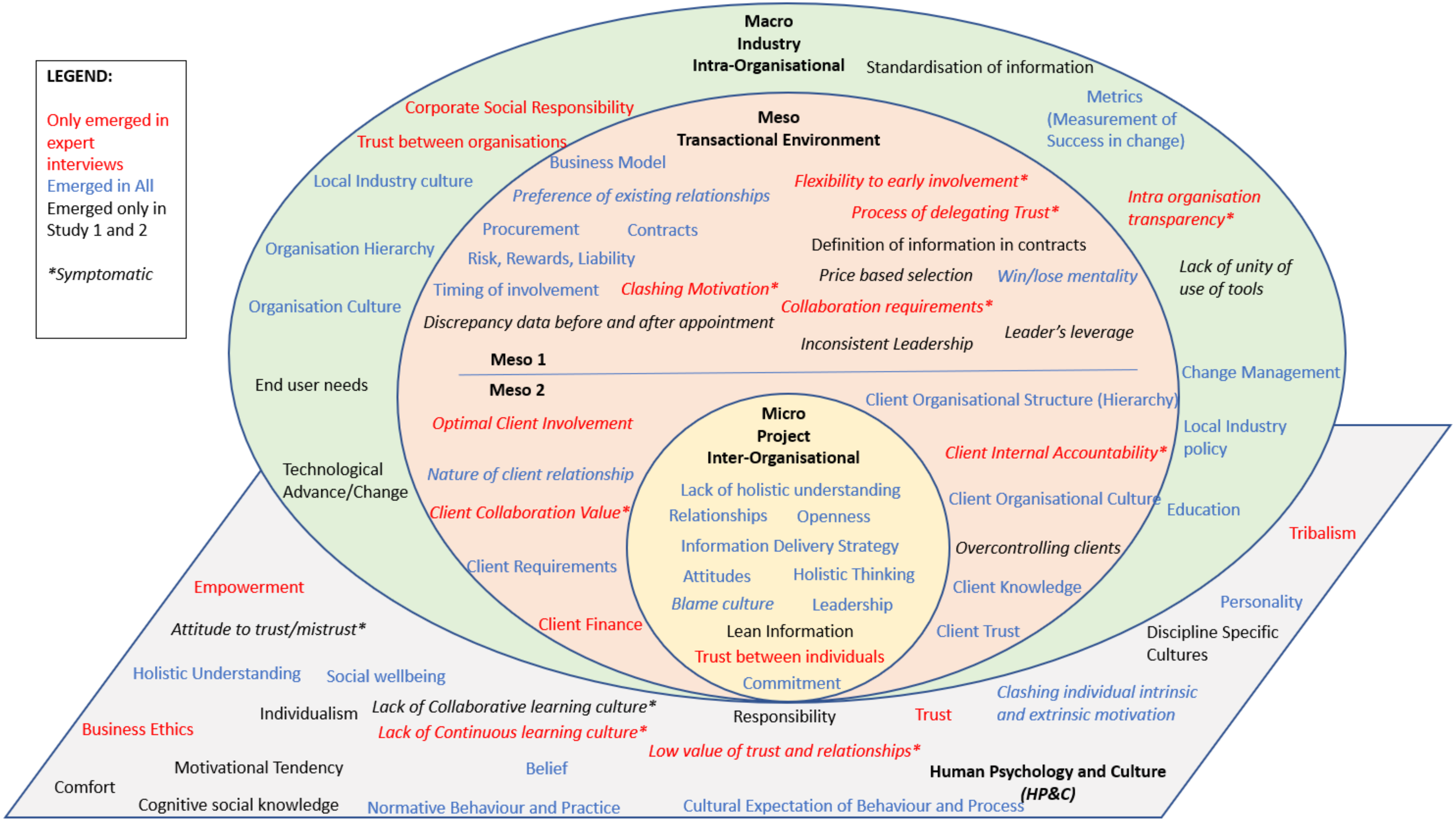


Figure 2: Categorisation of Factors from Empirical Evidence in Micro, Meso and Macro levels in the HMC-AEC-model

4.2 Motivation, Contracts and Social Climate

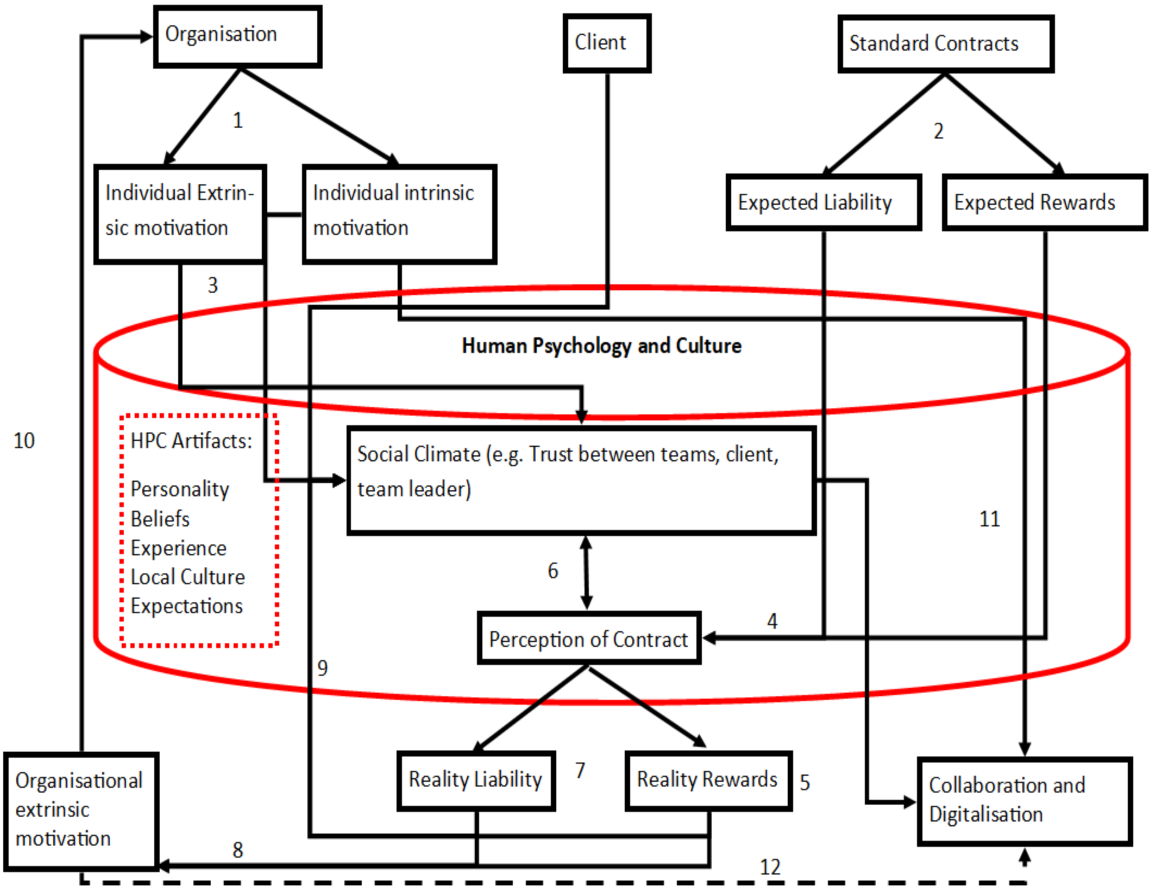


Figure 3: The Role of HP&C in Contracts and Motivation of Individuals and Organisations

Figure 3 shows the way the contract is perceived and motivates organisations and individuals which depends on the social climate and organisational factors. There is a difference between the expected liability and reward (2) and the realistic liability and reward (7) as contractual features are subjective (Bresnen & Marshall, 2000). These subjective elements are, for example, the definition of extra work. Due to the subjectivity, there is a dependence on the social climate of the project (6) which highlights the complexity of the HP&C level as it depends on people's perceptions. Rose and Manley (2011) conducted case study comparisons and found that the social climate is more important than the financial incentives set by contracts in motivating individuals, demonstrating the importance of the HP&C level of the model.

Since project level participants are hired by the firms and not the projects, this brings a higher order of complexity in studying motivation. The extrinsic organisation motivation from the project to the firm is translated to individual motivation dependent on the way that the organisation motivates its employees and varies between organisations (10, 1); this increases complexity, as it related organisational factors to the way a firm motivates its task force. In the grand scheme of collaboration and digitalisation, it is argued that innovative action is motivated intrinsically (11), see Barrett (2018). Extrinsic motivation is performance and profit oriented where typical firms put pressure on individuals to ensure their organisation is profitable from a single project. This is inconsistent with the needs of innovation activities which require more time and learning bringing a profit vs. professionalism dilemma in the behaviour of project level participants (Barrett, 2018); the individual extrinsic and intrinsic motivations are clashing dependent on organisational mechanisms to motivate individuals.

4.3 Comparison of Human Factor in AEC and Other Industries

The defense industry, unlike the AEC industry, has regulated processes with respect to human factors. The need for the AEC to have regulation of human factors was expressed by experts interviewed. Indeed, one expert explains the absurdity in 'a multimillion-pound project failing because of personality clashes'. An expert with experience in the defense industry explained there is need to consider human capability and mitigate risks from interactions between human capability and project processes. Regulation streamlines the process practitioners take to consider human capability, which brings greater unity in project risk perception. The abstract overview used by the HFI regulation is similar to the IDDS model (see Figure 4) but adds a foundational level referred to as the 'environment', which is dependent on human capability. In the IDDS model, human capability is captured within the 'collaborating people' part of the model. It is suggested that the human psychology and culture part of capability (environment) is also found to affect all parts of the model and therefore requires foundational setting as in the HFI regulation. However, human capability as in the HFI regulation goes beyond human psychology and culture, making the contribution of this paper visually represented in the abstract model below:

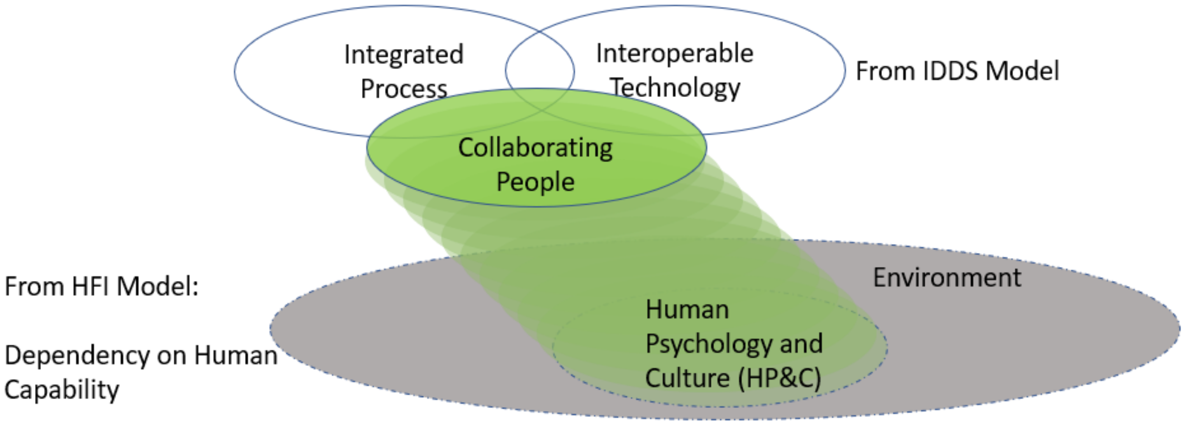


Figure 4: Contribution from Defence HFI to AEC IDDS perspective (adapted from Ministry of Defence, 2015; Owen et al., 2009)

The interpretive research presented both in this paper and in other literature, explain the need to consider the social and psychological dimensions in solution delivery (Barrett, 2018). Collaboration in healthcare requires the patient and the healthcare team to share a common understanding of the illness (i.e., to use the same model) or management may fail (Horowitz, Rein & Leventhal, 2004). Central to this exchange is trust (Zhixia & Mengchu, 2018). Similarly, in the AEC industry the client requires to have a similar thinking process to teams enabled by an open collaborative environment. However, as empirical evidence suggests, beliefs driven from experience and culture create a barrier between client and teams bringing about mistrust.

From healthcare, it is evident that the historically driven reductionist approach forms the norm in education and research and therefore in daily practice, however, interventions to encourage holistic thinking are in healthcare education based on the biopsychosocial approach. In the AEC industry and this research, education emerged in both Studies 1 and 2, and all experts explain the siloed nature of discipline specific education having an impact in inter-disciplinary solution delivery. This is reproduced from project to project in the design stage, leading to challenges identified in literature (Mêda, 2014); this was related to industry fragmentation and use of traditional contracts. The cause of this siloed nature is disputable; however, engineering courses are highly reductionist/positivist whereas architecture courses tend to be more interpretive according to experts. Furthermore, many educational institutions take on fragmented discipline specific education delivery. Therefore, knowledge transfer to practitioners from education is siloed; an expert explains that intern training at their firm is predominantly in negotiation and people skills to bridge the gap of human factor understanding and skills.

Although many scholars raised awareness and received credit in the healthcare sector about biopsychosocial model addressing missing parts of the biomedical model; a paradigm change has not yet occurred (Wade & Halligan, 2017). Similarly, in the AEC industry, firms are operating in a fragmented industry motivated to reduce risk. However, digitalization is suited by higher integrated environments bringing about a paradox in the industry both in behaviour of people and in business model innovation. The model presented in this paper can be utilized to raise awareness of the value of HP&C aspects both in research and practice. One expert explained the impact of the model as a pedagogic tool, to get students and practitioners to understand the bigger picture of their operations. Furthermore, as an outcome, AEC education could take on case study reflections, such as those performed in healthcare, to allow students to venture outside the discipline specific boundaries to raise awareness of otherwise hidden aspects.

The impact of the transactional Meso level is worth highlighting. For example, for a design team in traditional processes, the contractual outcome is the technical design rather than the built object. This restricts teams' capability to get involved in the built objects' development. Focusing on the built object would constitute a paradigm shift implying changes in designer culture. To the client/owner, it implies a new business culture, requires commitment and management knowledge. Schedules, motivation, work processes and stress can vary substantially depending of the client/owner's commitment to the project.

5. Closing Remarks

An interpretive, social scientific research project was used to understand the reality of collaborating teams. The reality-driven data was enabled by an unstructured format of interviews and focus groups with a central theme of collaboration. The external analysis model used predominantly in organisational science was found to best suit the nature of interactions between themes. The foundation for the Holistic Model for Collaboration in the AEC-industry (HMC-AEC) was introduced as a result of observed Micro, Meso and Macro dependency. These factors are human oriented and therefore categorized under Human Psychology and Culture (HP&C). The rooted nature of HP&C factors is as a result of limitations inflicted by human capabilities and means these factors need to be considered carefully when setting up and running a project. Furthermore, the HMC-AEC can raise awareness of the need to consider the nature of humans to practitioners and in future research; identifying the way that the Meso level can be set (e.g. contractual forms, client relationship management). In comparison to existing models of collaboration, the model is one of the first in the domain to place significance of people at the foundation. The high complexity of the origins of expectations and other human psychological and cultural aspects discussed here drive individuals to use belief-based heuristics as a default to make decisions. Therefore, to create enterprise in the industry, changes in beliefs need to accompany changes to process and technology. Ultimately, individuals need to know what to expect as any changes are not only organisational but also personal.

This study illustrates that the industry can learn new ways of understating collaboration (or HP&C) from other industries and unstructured approaches to data collection. There is a challenge to deal with the complexity in collaboration in a systematic professional manner. This study has demonstrated practical use of the HMC-AEC model to improve understanding of factors and their dependencies related to human capability by exemplifying dependencies between the human oriented factors (HP&C) and Micro, Meso and Macro levels. This reduction of complexity makes it possible to identify most relevant factors in a systematic and reality driven manner. The HMC-AEC model enables a foundation for professionals and educators in the AEC industry to turn otherwise complex multi-level phenomena regarding HP&C into manageable understanding and systematic improvements. The model also provides researchers with a holistic vision of the complexity of collaboration in practice; by considering multi-level factor dependencies exemplified here, methodological design can be envisioned and improved. Further research is required to extend this model from AEC to include owners and facilities management to cover the whole building lifecycle, to facilitate consistent and improved holistic perspective.

References

Ajzen, I. (1985). From intentions to actions: A theory of planned behavior. In *Action control* (pp. 11–39). Springer.

Barrett, J. E. (2018). An Exploratory Study of Collaboration In Built Environment Design Teams: A Social Psychology Perspective. University of Central Lancashire.

Bresnen, M., & Marshall, N. (2000). Motivation, commitment and the use of incentives in partnerships and alliances. *Construction Management and Economics*, *18*(5), 587–598.

Engel, G. L. (1977). The need for a new medical model: a challenge for biomedicine. *Science*, *196*(4286), 129–136.

Hjelseth, E. (2017). BIM Understanding and Activities. *WIT Transactions on The Built Environment*, *169*, 3–14.

Horowitz, C. R., Rein, S. B., & Leventhal, H. (2004). A story of maladies, misconceptions and mishaps: effective management of heart failure. *Social Science & Medicine*, *58*(3), 631–643.

Kleinman, A., Eisenberg, L., & Good, B. (2006). Culture, illness, and care: clinical lessons from anthropologic and cross-cultural research. *Focus*, *88*(1), 149–251.

McLeod, J., & Childs, S. (2013). The Cynefin framework: A tool for analyzing qualitative data in information science? *Library & Information Science Research*, *35*(4), 299–309. https://doi.org/https://doi.org/10.1016/j.lisr.2013.05.004

Mêda, P. (2014). Integrated Construction Organization-Contributions to the Portuguese Framework. Master Thesis in Civil Engineering, Faculty of Engineering of the University ….

Ministry of Defence. (2015). *JSP 912: Human Factors Integration in defence systems (Part 1: directive)*. Retrieved from https://www.gov.uk/government/publications/human-factors-integration-in-defence-systems-jsp-912

Owen, R. L., Amor, R., Dickinson, J., Prins, M., & Kiviniemi, A. (2013). Research roadmap report: Integrated Design and Delivery Solutions (IDDS).

Owen, R. L., Palmer, M. E., Dickinson, J. K., Tatum, C. B., Kazi, A. S., Amor, R., & Prins, M. (2009). CIB white paper on IDDS integrated design & delivery solutions.

Rose, T., & Manley, K. (2011). Motivation toward financial incentive goals on construction projects. *Journal of Business Research*, *64*(7), 765–773.

Sousa, H., & Mêda, P. (2012). Collaborative construction based on work breakdown structures. In *ECPPM 2012–9th European Conference on Product and Process Modelling* (pp. 839–845).

Sujan, S. F. (2019). *A holistic analysis of project level collaboration in the AEC industry (Unpublished)*. University of Liverpool.

Sujan, S. F., Kiviniemi, A., Jones, S. W., Wheatcroft, J. M., & Hjelseth, E. (2019). Common biases in client involved decision-making in the AEC industry. *Frontiers of Engineering Management*. https://link.springer.com/content/pdf/10.1007/s42524-019-0026-3.pdf

Sujan, S. F., Kiviniemi, A., Jones, S. W., Wheatcroft, J. M., Hjelseth, E., Mwiya, B., … Alhava, O. (2018). Holistic methodology to understand the complexity of collaboration in the construction process. In R. S. Jan Karlshoj (Ed.), *eWork and eBusiness in Architecture, Engineering and Construction*. Copenhagen: Taylor & Francis.

Taylor, J. (2005). Three perspectives on innovation in interorganizational networks: Systemic innovation, boundary object change, and the alignment of innovations and networks. *PhD, Stanford University, Stanford, CA*.

Van Notten, P. W. F., Rotmans, J., Van Asselt, M. B. A., & Rothman, D. S. (2003). An updated scenario typology. *Futures*, *35*(5), 423–443.

Wade, D. T., & Halligan, P. W. (2017). The biopsychosocial model of illness: a model whose time has come. SAGE Publications Sage UK: London, England.

Wildemuth, B. M. (2016). *Applications of social research methods to questions in information and library science*. ABC-CLIO.

Zhixia, C., & Mengchu, Z. (2018). Structure and Measurement of Doctor-Patient Trust and Its Integrated Model. *Journal of Psychological Science*, (1), 25.

A Framework for Product Recall in the Construction Industry

Richard Watson[1*], Mohamad Kassem[1], Jennifer Li[1]
[1]Faculty of Engineering and Environment, Northumbria University, Newcastle Upon Tyne NE1 8ST, UK
* email: richard.watson@northumbria.ac.uk

Abstract

The independent review into the UK Building Regulations and fire safety following the Grenfell Tower tragedy in 2017 highlighted significant failings in traceability of construction products used in the UK, noting that the construction industry is “significantly lagging behind many other sectors” in this respect. One of the key drivers behind the need for traceability is to support product recall, such as might be required in the event of the discovery of issues in product manufacturing, testing or as a result of inappropriate product specification or substitution.

This study investigates the need and benefits for a robust product recall system for the construction industry, develops a set of requirements for such a system, and proposes a framework for its implementation. The current state of the art for construction product recall is examined and compared to industries such as automotive and food where effective recall systems have been in place for a number of years. The particular requirements for traceability of products in the construction sector are defined and discussed. The framework for a construction product recall system was developed through a series of collaborative workshops with experts from industry and academia. This paper describes the framework and discusses the challenges facing its implementation. In particular, the paper discusses and compares in detail two approaches for product recall alerting; push and pull mechanisms. The paper concludes with the identification of areas for further investigation.

Keywords: traceability, construction products, product recall, Hackitt review, digital record.

1. Introduction

The Independent Review of Building Regulations, led by Dame Judith Hackitt following the Grenfell Tower tragedy, identified deep flaws in the UK regulatory system and determined that it was not fit for purpose (Hackitt, 2018). The review identified several areas where the construction industry lags behind others, and in particular emphasised the need for significant improvements to product testing, labelling and traceability, and implementation of a more effective product recall system.

Consumers are familiar with recall of products including high profile examples in the automotive, foodstuffs and consumer goods markets (Ahsan & Gunawan, 2018), (BBC, 2016). Given the potential impact of unsafe or faulty construction products it is, therefore, important to establish how the recall process for the industry can be enhanced to reduce risks to building occupants. This research explores the need for a recall system for construction products and reviews the current approaches employed in the industry. Recall systems in other sectors such as food and drink and automotive are reviewed and criteria for improving recall are established. A series of workshops were held with industry and academic experts from a range of different fields and product recall was identified as a key use case among the 63 that were identified in relation to the broader field of traceability and the digital record recommended in the Hackitt Review. The product recall use case was developed in detail and used as the basis on which to develop proposals for implementing an improved product recall system in the construction industry.

Section 2 discusses the need for product recall in the construction industry; section 3 reviews the current approach to product recall in the industry; section 4 presents the workshops and their outcomes; section 5 outlines the aims and requirements for an optimum product recall system for the construction industry drawing on learning from other industries; and sections 6 provides discussion, conclusions and next steps for the research.

2. The need for product recall in the construction industry

The principle reason for product recall in the construction industry is to protect people from the risks created when unsafe products are incorporated into buildings. An effective system can facilitate a timely and effective response to an issue in line with the definition in the Code of Practice for consumer product recalls, PAS 7100: 2018 (Department for Business Energy and Industrial Strategy, 2018).

Industries such as automotive, food and drink and consumer products have implemented legislation and systems for product recall to address some high-profile issues related to safety and quality. The main causes of product recall are safety and quality issues (Eilert, Jayachandran, Kalaignanam, & Swartz, 2017) which may be caused by failures in good manufacturing practice, incorrect labelling and packaging and the identification of conditions that can compromise safety such as contamination (Dabbene, Gay, & Tortia, 2014). Failures in design, problems with the material and unanticipated use (or misuse) are also identified as causes justifying product recall (Eilert et al., 2017). Berman (1999) also identified that new scientific information about the dangers from a product or material previously thought safe and failure to comply with safety standards as reasons for product recall(Berman, 1999)(Berman, 1999)(Berman, 1999)(Berman, 1999)(Berman, 1999)(Berman, 1999).

All of the above issues could potentially apply to construction products, creating risks that a recall system could mitigate. Examining literature and published recall notices there is existing evidence of the need for a product recall in the construction industry. For example, in her review of Building Regulations and Fire Safety following the Grenfell Tower tragedy, Dame Judith Hackitt noted cases of fire doors being marketed as fire resistant to 30 mins failing retesting and the issues with the aluminium composite material (ACM) in cladding used on many buildings including Grenfell Tower (Hackitt, 2018).

Examples of construction product related recalls identified on the OECD global product recall portal (OECD, 2019) include counterfeit products (including counterfeit fire resistant glazing), and products which did not meet the claimed fire resistance (class D against claimed class B). The portal contains a total of 231 product recall notices classified as building products (about 1% of the total 22,512 notices).

In Europe the rapid alert system for non-food consumer products, Rapex, covers consumer products that pose a serious risk to consumers. It aims to facilitate rapid exchange of information between member states about dangerous products and in 2018, more than 2250 alerts were raised. In May 2019, the Rapex system included a total of 107 notifications for construction products from 20 different countries (European commission, 2019).

Product safety is a significant potential issue in the construction industry. To reduce risks, construction products are tested and certified and under EU legislation and products requiring a CE mark must have a declaration of performance from the manufacturer (European Commission, 2019b). However, despite the safety and testing legislation and evident risks posed by unsafe products, there is currently no UK legislation for product recall in the construction sector.

3. Current approaches to product recall in the construction industry

In the absence of legislation for product recall in the construction industry there is no single, established system to support it. Some products may fall under the regulations aimed at protecting consumers, such as the UK General Product Safety Regulations 2005 that sets the requirements for products to be safe and conform with relevant standards. This legislation covers products that are "intended for consumers or likely…to be used by consumers" (The General Product Safety Regulations, 2005) and includes provision for an enforcement authority to serve a recall notice on a manufacturer where they have reasonable grounds to believe that a dangerous product has been supplied to consumers.

The construction industry relies on publicising recall notifications through websites such as Rapex and the OECD portal and sharing information between parties and trade associations. Electrical Safety First lists 12 construction product recalls on its website (Electrical Safety First, 2019). Bodies such as local trading standards offices may also issue product recall information (Chartered Trading Standards Institute, 2019) and the UK Association of Fire Investigators (UK Association of Fire Investigators, 2019). The construction industry shares some information about product recalls, for example through the Department of Health Estates and Facilities Alerts (Department of Health, 2019) and attendees at the research workshop noted that construction product manufacturers share technical bulletins with other organisations (including competitors) in order to help publicise unsafe products.

It is clear that there is a strong case for implementing a product recall system for the construction industry. Currently, in the event of design or production problems or any of the mentioned issues that might lead to product recall, the construction industry is not well served to protect the public from dangerous products. The number of different websites used to publicise unsafe products may cause confusion, and the current approach relies on building owners, managers, contractors and others in the industry proactively checking the published recall information. It also relies on these parties to have knowledge or accurate records to establish whether the effected product is in their building and then taking appropriate action.

4. Workshops

A series of 3 workshops were held with industry and academic experts to explore the requirements and develop proposals for a framework for a digital record that would support product traceability in the construction industry (Watson, Kassem, & Li, 2019). The first two workshops identified 63 use-cases that supported the need for establishing a traceability system; among these, product recall was identified as a key use-case for the industry that could be supported by a digital record. A definition of and a framework for the digital record are proposed in (Watson et al., 2019). A further workshop was held to examine this use-case in detail and to develop proposals for a product recall system.

Table 1: Sample of use-cases identified that could be supported by a Digital Record

	New buildings	Existing buildings
Design	• Brief from client to architect • Approved party to appointing party: submittals/approvals • Authority: manage inspections and issues relating to legislation	• Product used in building recalled • Designer: obtain as-built record of compliance • Surveyor to owner: condition survey of physical building
Construction	• Contractor: record installation, commissioning and variations • Ensuring site manager is receiving products on site in line with latest specifications • Change request from designer to contractor	• Contractor: safety during refit • Record original as-built specifications and condition • Re-roofing or roofing repairs
In-use	• Contractors: establishing suitability of replacement "parts" • Owner /contractor: usage changes or adaptation • Legislation changes	• Improved facilities management, proactive vs reactive • Owner: gain a "digital twin" for operations e.g. IoT, monitoring, bookings, route finder • Owner sells building

The use case addressed the recall of a dangerous gas boiler or a component within the boiler, and was considered in detail against a series of headings. The detailed use-case is shown in table 2.

The workshop participants considered the requirements and components of a traceability framework to facilitate product recall. Key aspects identified included: the need for unique identifiers for product types, assemblies, spaces and buildings; support for hierarchical (composition/decomposition) relationships between products; and supply chain information transfer and recording between parties. The workshops concluded that a digital record is essential to facilitate the traceability required for effective product recall.

Table 2: Use case for product recall

Title	Manage a product recall – a dangerous gas boiler or component within the boiler
Description	A serious fault is found in an installed product. The cause of the problem needs to be identified (design, installation, maintenance, product/component, process etc.) and immediate action needs to be taken to recall the affected products to mitigate the risks to personal safety.
Objective(s) Purpose for which the information is used	• Identify the duty-holders with risks • Manage and oversee the remediation of risk • Maintain data on corrective actions taken • Manage incidents
Stakeholders	• Duty-holders • Suppliers • Manufacturers • Joint Competent Authority • Occupants • Installer • Contractors

Information required and when required	• Number of products affected (e.g boilers) • Location of products (buildings, spaces etc.) • Products not yet sold • Parties to be contacted • Components ready to build the next product batch • Products already fixed/repaired (and which ones) • Products already scrapped (and which ones) • Product installer, installation method and approver
Sources of Information Sources of the required information. When created and by who? How is the information maintained?	• Suppliers' sales and ERP systems • Warrantee information • Retailers' and suppliers' records • Maintainers' records • Commissioning records • Common Data Environment (CDE) records • Design information • Building models (as built) • Handover data (COBie) • CAFM systems • FM tools • Asset registers
Information created / amended New information created or captured at this stage. How is this information maintained and by who?	• Records of what replaced • Disposal records • Incident records • Buildings/sites affected • Communication records • Remediation records • New asset information • People (installers) • New standards adhered to • Information created by repaired/owner/supplier/manufacturer
Future use cases How information created is used in future use cases	• Future occurrences of the issue • Service • Repair • Performance monitoring • Tennant information for use and operation
Security/Privacy considerations	• IoT presents a potential issue • Personal identifiable information, e.g owners, maintainers, legal entity
Access rights	• The appropriate party can access the appropriate data for the appropriate role
Benefits of digital record	• Digital Record provides the basis of traceability required • Transparency • Ability to query data • Time of response • Quantification of issue (e.g number of products affected) and certainty of action

Key challenges	• Transfer of ownership of the problem. • Define via dutyholders • Information veracity • Scope – defining what issues require recall • Openness and transparency vs security and privacy • Government defined and implemented solution

5. Aims and requirements of a construction product recall system

The principle aim for a product recall system is to protect people and buildings from unsafe products by facilitating a timely and effective response to an issue (Department for Business Energy and Industrial Strategy, 2018). The effectiveness of a product recall system can be attributed to four measures: i) the response rate, measured as the percentage of the total number of products affected that are recalled; ii) the accuracy of the recall – i.e. the degree to which only unsafe products are recalled rather than a larger recall that may include safe products (Dai, Tseng, & Zipkin, 2015) ; iii) the length of time taken to recall the maximum possible number of products; and iv) the cost of implementing the recall process (Ahsan & Gunawan, 2018) (excluding the costs of transportation, repair or disposal of unsafe products as these are particular to the nature of the product and safety issue).

Figures for recall effectiveness vary considerably. Response rates for product recalls are claimed to be in the region of 10-20% for electrical products in the UK (Electrical Safety First, 2019). Crumbly and Carter (2015) cite effectiveness of 40% for recall in the telecommunications industry, whereas response rates for vehicle recalls in the UK can be as high as 100% (Driver and Vehicle Standards Agency, 2018). The key difference in response rates is that vehicles are registered, enabling the registered keeper of the vehicle can be contacted in the event of recall. Consumer products are not typically registered, and Crumbly (2015) cites the lack of 'closed loop' systems as a contributory factor to lower recall effectiveness. Similarly, response rates for non-registered vehicle parts (such as tyres or components) tend to be much lower (52% for components recalled between 2014 and 2016 in the UK) (Driver and Vehicle Standards Agency, 2018).

Accuracy of product recall will primarily be affected by the ability to identify the specific products that need to be recalled and target the recall at just those products. Accuracy can be supported by uniquely identifying product types to a suitable level of granularity, recording sufficient meta-data about the product to determine whether a product has been affected by the factor causing the recall (manufacturing dates, component materials information, testing methods, testing organisation, lot or batch numbers) and having traceability mechanisms in place to establish where affected products are (so that recall requests are targeted rather than broadcast).

The speed of recall will be influenced by how quickly the location of affected products can be established and remedial activities instigated. The recall cost will be influenced by the accuracy with which products can be identified, whether location information is available and the mechanism used to contact the appropriate stakeholders; broadcast, push and pull mechanisms outlined below.

Based on the 4 measures of recall effectiveness above, the authors propose that an optimum product recall system should:

- *minimise the time and cost required to accurately trace every affected product to its location and*
- *alert the dutyholder for that location to the issue and the action(s) they should take.*

The authors consider location to include the location of a physical product in the supply chain or installed in a building and also to include the location of a digital representation of the product within the "information chain" of design and requirements data. The authors also adopt the Hackitt Review's definition of dutyholders as client, principal designer, designer, principal contractor and contractors as a minimum (Hackitt, 2018). The authors suggest that this list should be extended to include manufacturer, distributor and compliance agencies for the purposes of supporting product recall.

Adopting the above definition would require a product recall system that should:

- Alert designers and compliance agencies (such as building control) to a safety issue with a product (or product type), enabling them to remove that product from current design projects avoiding time and expense later in the project.
- Alert manufacturers suppliers and distributors, to withdraw products in the supply chain from sale.
- Alert contractors in order to prevent installation of unsafe products or remove those already installed.
- Alert clients and building occupants, to take appropriate actions.

Examining the requirements for a product recall system in more detail, four components need to be in place.

First, a mechanism for uniquely identifying products is required. This should support identification of:

i) generic product types (to facilitate recall of all products of the same type, that might have been manufactured by different companies) for example all warm-air hand driers manufactured to a particular standard.

ii) product types specific to a manufacturer. To facilitate recall of a specific product type for example when issues with design or manufacturing are discovered. Company ABC, dryer model HD-123

iii) a product instances. To facilitate recall of an engineered-to-order product and to track which instances of product have been successfully recalled or modified.

Second, additional data is required about the products at each of these three levels. At instance level, manufacturing information such as batch or lot information, manufacture date should be available to facilitate targeted recall. At manufacturer type level, metadata should include testing and compliance information to support recall in the event of discovery of issues with a particular test procedure or testing facility. This information is essential for recall accuracy, so that only products affected by the issue are recalled (Wowak, Craighead, & Ketchen, 2016), (Dai et al., 2015) and at the correct level (Dai et al., 2015).

Third, a mechanism is required to establish where products are, both in the supply chain so they can be withdrawn from sale and within buildings so they can be recalled. Within a building, this requires information linking a product component to any parent product (e.g. the internal motor to the hand dryer it is part of) then linking the parent product to the space it resides in (e.g. washroom 001) and the space to the building. This traceability information is critical to product recall in other industries enabling firms to determine the path a product has taken to reach its current location (Wowak et al., 2016).

Fourth, there needs to be a mechanism to directly alert the current owner or holder of the product to the recall. Three alerting mechanisms are identified:

i) 'broadcast' alerting. This approach is common with many current recall approaches due to the lack of mechanisms (such as registers) to link the product to a 'dutyholder' who can be contacted. Typically, broadcast alerting involves traditional advertising and social media which are the most common mechanisms through which consumers see or hear product recall information (traditional media 79.8%, online media 53.6%) (Ipsos, 2019). This option was discounted in the workshops due to the high costs, low response rates and slow performance.

ii) 'push' mechanisms. Response rates, accuracy and speed can be optimised, and recall costs reduced if alerts are directed only to dutyholders known to have one or more of the products affected. This is the mechanism employed in current vehicle recall systems, supported by vehicle identification linked to a register of current 'keepers'. For construction product recall this would require unique identification as described above together with registers of dutyholders, buildings and products within the buildings, and linking relationships to enable the dutyholder responsible for the effected product to be identified and contacted.

iii) 'pull' or 'look-up' mechanisms. An alternative approach to push alerting is for dutyholder systems to periodically check for issues by accessing recall information from a register of recalled products. An automated look-up system could offer the same improvements to response rates and accuracy as push alerts and dutyholder systems could check frequently enough to provide reasonable speed. A recalled product register could be held centrally or distributed (e.g. each manufacturer holds its own product recall information). Again, this approach relies on a system for unique identification of products. The workshop discussed the relative merits and drawbacks of both push and pull alerting.

Push alerts

The example of the automotive sector suggests that this approach can be effective, given the high recall response rates achieved for vehicles. However, this may be particular to vehicles, where owners need only register a small amount of information to enable them to be contacted and this is related to a single identified object (the vehicle) through one ID – the vehicle identification number (VIN). The manufacturer retains responsibility for managing the information about the component parts and the relationship of these to the car. As the manufacturer can theoretically record information identifying all of the component parts of every vehicle, they can push alerts out to registered keepers in the event of recall. A similar model exists for white goods and the "register my appliance" system (Association of manufacturers of domestic Appliances, 2019), but this is a partial solution as registration is voluntary so a combination of push and broadcast alerts have to be employed to improve response rates.

Adoption of this model for the construction industry would require registering all products. Registration could be held centrally (as with vehicles) or with the responsible manufacturer. Product registration could be the responsibility of the contractor at handover, or the building owner, but this will very likely represent a significant administrative burden unless automated through tagging of products (i.e. radio frequency identification) and scanning at the point of installation.

Such a system would require registers of products, assemblies, spaces, buildings and owners, facilitated through unique ID systems for each. Relationships recorded against these IDs could be used to establish which products are contained in which spaces of buildings and who the building owner is. Product attributes can be stored against both product type and instance.

The workshops identified a number of issues with this approach. If product manufactures are responsible for maintaining the product registers, mechanisms would need to be put in place to transfer the register to another body in the event of a manufacturer ceasing to trade. The alternative is to have centrally held registers, independent of the manufacturers. Long-term maintenance of data currency (required due to the lifespan of most buildings) is also a significant issue. Buildings are adapted and products are frequently maintained, repaired and replaced in buildings and to maintain accurate product registers would require building owners to update the registers by sending information about all changes to the register keepers, which is also a significant burden. Workshop participants considered data security as a potential issue for central registers that recorded the component products in all buildings and the sheer scale of information storage requirements is likely to present a significant challenge.

Pull mechanisms

A framework to support pull notification of recall was also considered. Workshop participants noted that many building owners will already have CAFM or other management systems that record information about the products within a building. The Hackitt Review also recommends that owners, as dutyholders, should be required to maintain accurate digital records of a building. A framework could employ a central product database to store information about recalled products with unique identifiers (UIDs) associated with all product types. Assigning the same product type UIDs in dutyholders' digital record systems would support recall systems 'polling' (making a regular query of) the central product database for recall updates on a regular basis.

This approach requires manufacturers to register product types with the database. The database could potentially be developed as an extension of the CE marking system that operates in Europe (European Commission, 2019a), to create a national product database (NPD). Issues potentially leading to a product recall could be raised with a manufacturer or the body responsible for the (NPD). A UID associated with a product supports backwards traceability to identify the manufacturer. If determined necessary, a recall is initiated by flagging the product type in the NPD. Dutyholders would be alerted if affected products are identified within their digital record when it next polls the NPD. This approach provides clear lines of responsibility and data ownership in line with Hackitt Review recommendations for dutyholder responsibilities. Dutyholders have long-term responsibility to maintain their digital record data, and this is managed within their systems rather than external registers. Manufacturers ceasing to trade remains an issue with this model, but the body responsible for maintaining the national product database could continue to provide a mechanism for raising recall alerts.

6. Discussion and Conclusions

The importance of an effective systems of product recall in the construction industry is identified in the Hackitt Review and reinforced by analysis of the published construction product recall notices (Hackitt, 2018) (OECD, 2019). Despite the evident risks that unsafe construction products raise, the current system is not optimised and relies on an ad-hoc mixture of technical bulletins and posting alerts on several product recall websites, many of which are aimed at consumers rather than trade or professional users. Studies have demonstrated the ineffectiveness of broadcast alert systems (Crumbly & Carter, 2015) in terms of response rates, accuracy, speed and cost. More effective recall systems such as for vehicles (Driver and Vehicle Standards Agency, 2018) employ mechanisms that record a link between the product and the registered keeper.

The researchers explored how such links could be created and maintained for construction products in order to support and optimise product recall systems. Through workshops with industry and academic experts, two models evolved. Both approaches rely on establishing an effective system of unique IDs for construction products, and locations (including spaces and buildings). The first model considered a series of registers for products, spaces, buildings and stakeholders linked via the UID system to support 'push' notifications of recall information. The second model was based around the development of a National Product Database that could be 'polled' by dutyholders' systems for information periodically or at specific events to check for recalls. Either system would be a substantial undertaking for the construction industry and require agreement on a set of standards to include UID system and corresponding digital and physical identifiers (i.e. bar codes or RFID), product classification and the mandatory attribute data to be stored. However, existing technologies and research have strong potential to form the basis of such a system. The UID system could be based on the GS1 Global Trade Item Number (GTIN) (GS1, 2019) or research into unique product identifiers (UK Research and Innovation, 2015) and the construction industry has a comprehensive classification scheme, Uniclass 2015 (NBS, 2019a). Mandatory product attribute data could draw on the COBie standard (British Standards Institute, 2014), the product data templates within the NBS BIM toolkit (NBS, 2019b) and CE marking data.

With a NPD the need to trace ownership through supply, construction and in-use chains is reduced as long as the digital record systems employed by each dutyholder are linked to the NPD via UIDs to request updates/alerts. The responsibility for awareness of product safety is altered and becomes one stakeholder checking (via automated mechanisms) rather than the current ad hoc broadcast mechanisms. A NPD can support notification of a product issue to any linked system, thus supporting alerts to all dutyholders and at all stages of a project lifecycle. For example, a designer could check the products within a BIM model against the NPD alerts at key stages in the design process. Compliance checking could also include processes to check products against the recall information in the NDP.

Workshop delegates favoured the pull-alert approach as providing clear lines of responsibility, aligning responsibility for data maintenance of the digital record with asset ownership and controlling access to the digital record for security and privacy purposes.

Other benefits for a central NPD are also identified including: the ability to update (pull) other information (new operating or maintenance instructions for example) from the NPD, potential benefit to the supply chain of common product-type information improving communication effectiveness; reducing unauthorised product substitution and use of counterfeit products as noted in a New Zealand feasibility study (Dowdell, Page, & Curtis, 2017).

Further research will review NPD in other sectors and explore the feasibility and wider benefits of this approach in more detail. The proposals for product recall systems identified in this study will be evaluated against the other use-cases identified for the digital record and traceability, in order to establish whether they provide support for wider requirements beyond product recall.

References

Ahsan, K., & Gunawan, I. (2018). Analysis of Product Recalls: Identification of Recall Initiators and Causes of Recall. *Operations and Supply Chain Management: An International Journal*, *7*(3), 97. https://doi.org/10.31387/oscm0180115

Association of manufacturers of domestic Appliances. (2019). Register my applicance. Retrieved May 24, 2019, from https://www.registermyappliance.org.uk/

BBC. (2016). Samsung recalls Note 7 flagship over explosive batteries. Retrieved May 24, 2019, from https://www.bbc.co.uk/news/business-37253742

Berman, B. (1999). Planning for the inevitable product recall. *Business Horizons*, *42*(2), 69–78. https://doi.org/10.1016/S0007-6813(99)80011-1

British Standards Institute. (2014). BS 1192-4:2014 Collaborative production of information Part 4 : Fulfilling employer' s information exchange requirements using COBie - Code of practice. *British Standards Institute*, 58. Retrieved from http://shop.bsigroup.com/forms/BS-1192-4/

Chartered Trading Standards Institute. (2019). Product Recalls. Retrieved May 24, 2019, from https://www.tradingstandards.uk/consumers/product-recalls

Crumbly, J., & Carter, L. (2015). The impact of information technology on product recalls: Exploring the role of the six "ts" of supply chain management. *Production Planning and Control*, *26*(12), 958–968. https://doi.org/10.1080/09537287.2015.1009521

Dabbene, F., Gay, P., & Tortia, C. (2014). Traceability issues in food supply chain management: A review. *Biosystems Engineering*, *120*, 65–80. https://doi.org/10.1016/j.biosystemseng.2013.09.006

Dai, H., Tseng, M. M., & Zipkin, P. H. (2015). Design of traceability systems for product recall. *International Journal of Production Research*, *53*(2), 511–531. https://doi.org/10.1080/00207543.2014.955922

Department for Business Energy and Industrial Strategy. (2018). *PAS 7100:2018 Supporting better product recalls. Code of practice on consumer product safety related recalls and other corrective action*. BSI.

Department of Health. (2019). Estates and facilities alerts. Retrieved May 24, 2019, from https://www.health-ni.gov.uk/articles/niaic-estates-and-facilities-alerts

Dowdell, D., Page, I., & Curtis, M. (2017). *Electronic traceability of New Zealand construction products : Feasibility and opportunities*.

Driver and Vehicle Standards Agency. (2018). Safety recall response rates for closed recalls. Retrieved May 24, 2019, from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/527208/List_of_Registered_Providers_1_June_2016.csv/preview

Eilert, M., Jayachandran, S., Kalaignanam, K., & Swartz, T. A. (2017). Does it Pay to Recall your Product Early? An Empirical Investigation in the Automobile Industry. *Journal of Marketing*, *81*(3), 111–129. https://doi.org/10.1509/jm.15.0074

Electrical Safety First. (2019). Recalled Construction Products. Retrieved May 24, 2014, from https://www.electricalsafetyfirst.org.uk/product-recalls/categories/construction-products/#Results

European commission. (2019). Safety Gate: the rapid alert system for dangerous non-food products. Retrieved May 24, 2019, from https://ec.europa.eu/consumers/consumers_safety/safety_products/rapex/alerts/repository/content/pages/rapex/index_en.htm

European Commission. (2019a). CE Marking. Retrieved May 24, 2019, from https://ec.europa.eu/growth/single-market/ce-marking_en

European Commission. (2019b). Construction Product Regulations (CPR). Retrieved May 24, 2019, from http://ec.europa.eu/growth/sectors/construction/product-regulation_en

GS1. (2019). Global Trade Item Number (GTIN). Retrieved May 24, 2019, from https://www.gs1.org/standards/id-keys/gtin

Hackitt, J. (2018). *Building a safer future - Independent Review of Building Regulations and Fire Safety: Final Report*. https://doi.org/ID CCS1117446840

Ipsos. (2019). *Survey on consumer behaviour and product recalls effectiveness: Final Report*. https://doi.org/10.2818/646367

NBS. (2019a). Classification, Uniclass 2015. Retrieved May 24, 2019, from https://toolkit.thenbs.com/articles/classification

NBS. (2019b). Product data templates for manufacturers. Retrieved May 24, 2019, from https://toolkit.thenbs.com/articles/pdts

OECD. (2019). Global portal on product recalls (OECD). Retrieved May 25, 2019, from https://globalrecalls.oecd.org/#/?gs1-gpc-segment=83000000

The General Product Safety Regulations. , Pub. L. No. 1803 (2005).

UK Association of Fire Investigators. (2019). Product recalls. Retrieved May 24, 2019, from https://www.uk-afi.org/product-recall

UK Research and Innovation. (2015). RIBA Enterprises Ltd., Persistent Digital Identifiers for Construction Products. Retrieved May 24, 2019, from https://gtr.ukri.org/projects?ref=102057

Watson, R., Kassem, M., & Li, J. (2019). Traceability for built assets: proposed framework for a Digital Record. *Proceedings of the Creative Construction Conference 2019, Budapest*. Budapest: Diamond Congress Ltd.

Wowak, K. D., Craighead, C. W., & Ketchen, D. J. (2016). Tracing Bad Products in Supply Chains: The Roles of Temporality, Supply Chain Permeation, and Product Information Ambiguity. *Journal of Business Logistics*, *37*(2), 132–151. https://doi.org/10.1111/jbl.12125

A Study on Establishing the Optimal Planning and Design Criteria for the Intensive Care Unit of Hospital in Taiwan

Shih-Yuan Shao*, Chun-Ta Tzeng

* email: 891025@mail.chimei.org.tw

Abstract

ICU space design is related to the quality of medical care and the integration of multidisciplinary profession. However, there are still no domestic planning and design guidelines in Taiwan currently. The Modified Delphi Method is a research methodology based on the expert's independent judgement, the structured information communication and the systematic judgement process. To promote the quality of decision-making, it is supplemented by scientific statistical methods. As the basis for the first round of the Delphi Questionnaire, this study has developed the first questionnaire based on literatures that proposes 31 important score items and 14 selective items for planning and design elements of ICU. Further we select 20 experts to participate in this Delphi research whom including hospital decision-makers, ICU attending physicians and their teams, and ICU ward nursing heads. Finally, the study statistics use the Quartile as a consensus function to analyze whether the expert opinions converges.

Including the 45 items, the analysis results show that the overall consent convergence rate of experts was 95.56% and 43 items reach agreement in three groups by the Kruskal-Wallis test. The more strict consensus standards are adopted among the 43 items for selection ICU design criteria, this study defined Q.D.$\leqq$0.60 is “high consensus”, Q1$\geqq$4, Q3=5 is “very important”, and P$\geqq$0.75 is “consensus standard” for select items. It summarizes the 25 key points of its optimal ICU design guidelines, and those according to strengthening infection control, improving care efficiency and appropriate environmental design.

Keywords: Hospital Architecture, ICU Planning and Design, Modified Delphi Method

Introduction

The definition and development of Critical Care Medicine is an important milestone in the modern medicine. It originated from Armenian War in 1850. The pioneer of modern nursing, Ms. Nightingale, believes that the injured soldier should be placed in a nearby nursing station for immediate and adequate care. In 1923, Dr. Walter Dandy set up a post-brain surgery care unit at John Hopkins Hospital in the United States, which was directly cared for by the neurosurgical team to form the prototype of a modern intensive care unit. In the 1950s, the University of Southern California officially defined the critical care. That is the care required active life monitoring and additional support for patients who were life-threatening due to illness or trauma. In order to perform life monitoring and support treatment immediately and effectively, the hospital building evolution is the establishment of a special site in the hospital, the so-called Intensive Care Unit (ICU). (G. Ristagno and M. H. Weil, 2009)

With the advancement of intensive medicine, the hospital's ICU is not only a site or a unit in the hospital, but also an advancement in medical specialties and an important issue for hospital operations. The success of ICU planning depends on the consistent design philosophy and clinical goals of the intensive care team and hospital decision makers. Neil A. Halpern (2014) argues that the ICU plan has four initial core principles: First, the ICU is a semi-autonomous small hospital. Second, its design is an complex and time-consuming process needed multidisciplinary integration. Third, the success of the design depends on the function Innovation, the space appropriation, the equipment management and cost constraints balance. Final, the safety of patients, medical staffs, families and the security of instruments and supplies must be considered into the design of the treatment environment.

This study intends to use the Modified Delphi Method to obtain the final professional consensus on this complex issue. It should reduce the repeated communication and the revision in the design process between the medical care team and the design planning team. In additional, the method assemble the literature also can explore the trends in ICU planning in the world. Through qualitative and quantity research, structured experts information circulation and systematic experts judgment process, this methodology expect to obtain the guidelines about the ICU design criteria in Taiwan. The research results can be used as an important reference and guideline in the concept and practice for Taiwan hospital ICU design.

2. Material

2.1 Modified Delphi Method

Delphi Method originated from Rand Corporation in 1948. It under the auspices of the US Air Force named "Project Delphi." For more than 60 years, it has evolved into a research method that draws on the advantages of both questionnaires and conference discussions. There are several main basic principles of the Delphi Law: (1) "anonymity group decision making": participants strictly abide by the principle of anonymity; (2) "control feedback principle": the questionnaire is repeated after each round of questionnaires is collected. The results of the survey must be returned to the panelists and as a revised reference for the next round. (3) "Expert Consensus": Experts can adhere to or modify their opinions according to the last feedback trends. The researchers use statistical methods to judge whether expert opinions converge and the project will proceed to be consistent until the research reach consensus.

Therefore, the research execution of the Delphi Method is different from the other general questionnaire survey methods. The main points are: (1) The object selected by Delphi Method is an expert, so it is a small sample survey. The background of the expert should be closely related to the professionalism, decision-making, forward-looking and predictive nature of the research topic. The number of experts is acceptable to 10 to 50 people (Jones and Twiss, 1978), but the experts who continue to participate need at least 10 people to reduce the error between members. (Reza and Vassilis, 1988) (2) The test procedure conducted by Delphi Method is repeated for several rounds with three rounds or more until the expert opinions converges. (3) To establish a "consensus function" for the expert opinions, it is necessary to set the standard. It mainly includes: the consistency test of the experts on individual items, the consistency of the experts on the overall questionnaire, and the consistency of the different groups of experts on each question item.

The first round is an open questionnaire in the traditional Delphi method. This questionnaire is designed by the researcher who assembled the expert conclusions through their main axis of the research problem description. However, in this first stage, the open opinions summarized and edited were complicated and the questionnaire recovery rate was often lower and lower. Therefore, the Modified Delphi method develop to use the literature collection to replace the expert opinions description for the first stage questionnaire design. In the second round, the post-recycling opinion was analyzed. The contents were also released, added and deleted again to generate a third round of questionnaire. This is repeated until the expert opinion converges.

This study was carried out using the Modified Delphi method. After assembling the references and literature about the design elements for ICU, this study find that there are four key points for ICU design. These focus are “hospital decision-making perspectives” (including setting address, area size, construction cost, unit size and so on),“infection control views” (including how to reduce the hospital infection rate through space design, air pressure of the ward, HAVC system and so on), “clinical care perspective”(including the design of the nursing station, the planning of the service support area, the ward working line and so on) and“user perspective”(taking into account ergonomics, the needs of the staff considerations in the work area as well as the social support for patient's family).

The ICU planning can be roughly divided into two levels. The first level is the overall planning trend of the ward and the second level is the design principle of the ward space. The overall planning trend of the ward is mainly at the decision-making level, including ward attributes, ward size, regional configuration, infection control strategy, cost considerations and so on. The spatial design content includes ward design, support area design and family area design and so on. Incorporating foreign researches, winning design cases and their proposed conclusions, this study developed the main content of the first round questionnaire. Through the selection of experts, the research will proceed expert opinion surveys and statistical analysis of more than two rounds.

2.2 Experts selection for Modified Delphi Method

Valentin and Ferdinande (2011) believe that the participators for planning of ICU should include hospital managers and superintendents, intensive care unit director, attending physician and nursing chief, infection controller, architect and medical engineer. Some documents believe that the design of the ICU should involve family members. However, because the family members of the patients did not understand the professional medical care process, so it was excluded from this study for the experts group.

According to Valentin and Ferdinande's recommendations, this study selected 20 senior clinical directors to participate in this study who are from three hospital levels according with the evaluation system of Taiwan Health and Welfare Ministry. Among the 20 experts, there are 6 hospital decision-makers, 6 senior attending physicians, infection controllers, senior hospital construction engineering supervisors and 8 ICU nursing supervisors. See Table 1 for the experts details of their hospital level, position, clinical work experience, and ICU qualifications.

Table 1 the Experts List and their Qualifications

Category	Number	Current Position	Work experience	ICU experience
Hospital Decision Maker	A1	Medical Center Deputy Superintendent	＞30 years	10 years
	A2	Region Hospital Deputy Superintendent	＞30 years	25 years
	A3	Community Hospital Deputy Superintendent	＞30 years	(Orthopedist)
	A4	Region Hospital Teaching Superintendent	＞30 years	4 years
	A5	Medical Center Nursing Superintendent	＞30 years	16 years
	A6	Senior Hospital Design Planning Supervisor	＞30 years	(Architect)

Medical Staff and the Team in ICU	B1	Region Hospital ICU Doctor	＞20 years	15 years
	B2	Medical Center ICU Doctor	＞15 years	12 years
	B3	Community Hospital ICU Director (Doctor)	＞15 years	10 years
	B4	Medical Center ICU Doctor	＞15 years	12 years
	B5	Community Hospital Director (Doctor)	＞15 years	3 years
	B6	Community Hospital infection control staff	＞20 years	(Infection controller)
Nursing Head in ICU	C1	Medical Center Nursing Supervisor	＞20 years	20 years
	C2	Community Hospital ICU Nursing Head	＞20 years	15 years
	C3	Community Hospital ICU Nursing Head	＞20 years	7 years
	C4	Medical Center Surgical ICU Nursing Head	＞20 years	20 years
	C5	Medical Center Nurology ICU Nursing Head	＞20 years	22 years
	C6	Medical Center Medicine ICU Nursing Head	＞20 years	14 years
	C7	Medical Center Medicine ICU Nursing Head	＞20 years	19 years
	C8	Medical Center Medicine ICU Nursing Head	＞20 years	7 years

2.3 Statistical method for consensus function selection

In the Delphi research, there is still no clearly defined consistency standard about the “consensus function”. We can select mode, median or quartile as the consensus function depending on the needs and the purpose of individual research. (Anne et al, 1994) Therefore, in this study defines the consensus function for the "selective items" that are not sorted with more than 51% of experts agreement.(McKenng , 1994) Further, if more than 75% experts of the same opinion，this study is considered to reach a “consensus standard”.(Murry and Hommons,1993).

In the “importance score items” that are sorted, this study uses Quartile to eliminate the influence of extreme values as the consensus function. This study analysis the first quartile (First Quartile; Q1 indicates) and the third quartile (Third Quartile; Q3 indicates) for each item. If Q1≧3, Q3=4, it is defined that this item is “important”. If Q1≧4, Q3=5, it means “this item is very important” in this study.(Huang Youjie, Luo Shaolin, 2001)

Further, this study uses quartile deviation(Quartile Deviation; Q.D. indicates) as the basis for verification on the overall experts opinion. The calculation formula of Q.D. is one-half the difference between the Q1 and Q3. The smaller the Q.D. value, the smaller the difference in each one and the higher degree of consensus in Delphi research. This study use Likert Scale and analysis the quartile for the consensus function value. If Q.D.≦0.6, it means that the expert opinion reaches “high consensus”; While 0.6<Q.D.≦1.0 means “moderate consensus”; Q.D.>1.0 means “not reached consensus”. (Yang Yizhen, 1999) Because the Delphi research conducted many times, experts with shallower opinions would change their opinions. It will get the median finally which is close to the "true value" of the overall opinion (Li Guozhong, 1999)

Finally, this study will end the survey just when more than 80% of the questionnaire items reach QD≦0.6 as the overall consistency and opinion convergence (Mead, 1992) In addition, in order to understand the similarities and differences between the three groups of experts opinion about ICU design planning, this study also carried out the K-W test (Kruskal-Wallis test) for the consistence test for "hospital decision-making executives", "ICU attending physicians and their teams" and "ICU ward nurse supervisors".

Results

3.1 Questionnaire recovery results

The first round of the questionnaire was completed from March 20 to April 30, 2017. Twenty questionnaires were all collected, but two were partially missing. As a analysis result of the overall 43 items, 4 "selective items" and 6 "importance score items" did not converge; the overall consistency ratio was 79.07% (<80%). It didn't reach the convergence. Therefore, the study feedback the results to the 20 experts by illustrating the P value and Q.D. value in the first round questionnaire items as the second round reference, and the second round of questionnaires was issued on May 10, 2017.

The second round questionnaire also summarize the open opinions of the first round into the second round questionnaire content. Two items are added: "There is a hospice care zone in the vicinity of the ICU" and "There is a CT room in the ICU for avoiding frequent movements just as those multiple trauma patients." After theses increase, the total number of items in the second questionnaire reaches 45.

The second round of the questionnaire was completed from May 10 to June 30, 2017. Eighteen questionnaires were recovered and the recovery rate was 90%. As a result of the overall analysis, only 2 of the 45 items have not reached convergence. These 2 items are "the best area of each bed"(P＜0.5) and "setting the shower room for man and women separately " (QD=1). The overall opinions convergence ratio is 95.56% which meets Mead's definition of consistency verification standard for more than 80% of the items. The survey is ended and the statistical analysis results of the overall "selective items" are shown in Table 2 an "importance score items" are shown in Table 3.

3.2 Statistical Analysis Results

In the "Selective Item", 13 of the 14 items have reached consensus that these opinions are considered to be a consensus as discussed by McKenng (1994). Further, there are 11 items that more than 75% experts express the same opinion reveal the opinions convergence in the view of Murry and Hommons (1993). See the Table 2 for details. The p values of these 11 items of ICU planning consistency opinions are indicated in bold in the Table.

According to Q.D.$\leqq$0.6 as the expert opinion reached "high consensus" and while Q1$\geqq$4, and Q3=5, it indicates the item meets the definition of "very important", the results of the second round found that 30 of the 31 importance scoring items have reached "high consensus", and 18 of them were met with the definition of "very important". Further chose the average score (μ value)> 4.5 as the "most important consensus", there are five planning content shown respectively: (1) each bed of the life support system should have a warning system linked to the nursing station (μ = 4.9444), (2) the most important factor of the ICU layout is considered the patient care field of vision linked with medical staff care movement line (μ = 4.8889), (3) ICU should design a multi-function room for staff conference, visit discussion, teaching activities and so on. (μ = 4.6667 (4) The Infection Control Hazard Assessment (ICRA) is an important consideration for the ICU's construction or renovation (μ=4.61). (5) The wash sink should be located at the entrance of the ward, or at the end of the bed. (μ=4.5556). The μ value and Q.D. values of these items are indicated in bold in the Table 3.

Table 2 Statistical Results of 14 "Selective Items" in the two rounds of Delphi Research

	ICU design factors-- "Selective Items" in the Delphi questionnaire	1st Round	2nd Round
		P(Proportion)	P(Proportion)
	Part 1--Overall planning trend		
1	You will suggest that construct an ICU is better than renovation.	0.8947	**1.0000**
2	You will suggest that the 'single specialty' ICU is better than 'general' ICU for the quality of medical care.	0.8947	**0.9444**

3	The optimum scale for an unit is 10-19 beds.	0.7368	**1.0000**
4	The ratio of negative pressure bed in an unit is at least 1:10.	**0.3684***	0.7222
5	The optimum layout for an unit is “racetrack”, better than “parallel corridor open”,“cruciform” and ‘radial’.	0.5263	**0.9444**
	Part 2--Space design principle		
	【A 】Ward Design		
1	Double compartment for each bed (no door) is the best for the ward.	**0.5***	0.5556
2	For a separate compartment of each bed, the optimal design for the care station should be a "4 bed module".	0.55	**0.7778**
3	The optimum size of each bed is : 9-10㎡ , or11~15㎡, or16-20㎡, or 21-25㎡, or over 25㎡ ?	**0.5<***	**0.5<***
4	Patient life support systems and medical instrument systems use the cantilevered medical columns preferably instead of power column on the headwall.	0.85	**0.8824**
	【B 】Support Service Area Design		
1	The design of the nursing station should be a decentralized style for the higher proximity and efficiency of the nursing care.	0.95	**1.0000**
2	The design of the support service area required by the care team should be the Central Care Station arrange in pair the Observatory	**0.5<***	**0.8333**
3	The support service space should be dispersed in other appropriate spaces in the ward, taking into account the efficiency of use.	0.65	**0.9444**
	【C 】Family Area Design		
1	The family waiting area is recommended to be located outside the ICU (considering family members will interrupt treatment, initiate infection, bring noise, etc.)	0.95	**1.0000**
2	It is not suitable for family areas in the ward to set companion beds, clothing cabinets, tables and chairs, etc.	0.80	**0.8824**

* **sign indicates**: the ratio value P is less than 0.51, and the expert opinion does not converge. McKenng (1994)

Table 3 Statistical Results of 31 "Importance Score Items" in the two rounds of Delphi Research

	ICU design factors-- "Importance Score Items" in the Delphi questionnaire	1st Round		2nd Round	
		μ	Q.D	μ	Q.D
	Part 1--Overall planning trend				
1	Infection Control Hazard Assessment is important for new ICU construction.	4.95	0	**4.61**	0
2	Cost consideration is important for ICU construction or renovation.	3.70	0.5	3.778	0
3	Patient distribution and disease pattern is important for an ICU whether	4.15	0.125	3.944	0

	construction or renovation.				
4	ICU with a single specialty attribute is safer for ICU patient care.	4.10	0.5	4.444	0.5
5	ICU with a single specialty attribute is more efficient for management	4.10	0.5	4.389	0.5
6	Patient care vision and medical staff working line are the important considerations for the overall ICU layout.	4.85	0	**4.889**	0
	Part 2--Space design principle				
【A 】Ward Design					
1	The bedside of the bed should be at least 60 cm away from the wall.	4.10	0.5	4.167	0.5
2	The end of the bed should be at least 150 cm away from the wall, 150 cm on the rotating side and 120 cm on the non-rotating side.	4.40	0.5	4.389	0.5
3	The cantilevered medical power columns is more proximity and efficiency than the power column on the headwall.	3.95	0	4.278	0.5
4	Cantilever medical column has architectural considerations.	4.30	0.5	4.333	0.5
5	Each bed area should have a toilet to handle the patient's blood and fluids.	3.70	0.5	3.167	0.5
6	Washing sink should be located at the entrance or at the end of the bed.	4.60	0.5	**4.556**	0.5
7	Each bed should have an ringing bell (calling bell).	4.60	0.5	4.333	0.5
8	Life support alarm system of each bed should be linked with station.	4.90	0	**4.944**	0
9	Each unit ICU ward should have natural lighting and out-of-window views.	4.35	0.5	4.333	0.5
10	There is a hospice care zone in the vicinity of the ICU.			3.889	0.375
11	There is a CT room in the ICU for avoiding frequent movements just as those multiple trauma patients.			3.611	0.5
【B 】Support Service Area Design					
1	The nursing station should have a broadcasting system.	3.95	0.625*	3.611	0.5
2	Have a superintendent office.	4.15	0.625*	4.167	0.5
3	Setting the shower room for man and women separately	4.05	0.625*	4.000	0
4	Large instrument placement area should be set.	4.50	0.5	4.333	0.5
5	A multi-function room should be setted for staff conference, visit discussion, teaching activities and so on.	4.55	0.5	**4.667**	0.5
6	There should be a lounge room for dining or rest.	4.50	0.5	4.278	0.5
【C 】Family Area Design					
1	The number of waiting chairs and beds should be at least 1.5:1 .	3.95	**0.75***	3.765	0.5
2	The design of this area should take into account the privacy.	4.37	0.5	4.000	**1.0***
3	This area has a toilet or there is a neighboring toilet available.	4.37	0.5	4.235	0.5
4	This area has a lounge room.	4.00	**0.75***	3.941	0
5	This area has a sleep room.	3.53	0.5	3.375	0.5
6	This area has a medical counseling room.	4.37	**0.75***	4.412	0.5
7	This area has a dietician room.	3.16	0.5	3.000	0.25
8	This area has a laundry room.	3.26	0.5	2.563	0.5

***sign indicates**: the ratio value Q.D.＞0.6 indicates the expert opinion does not converge.

The value show as the bold indicates the most five important opinions in this survey.

This study further analyze whether significant differences in the planning and design opinions between the three groups of experts by the Kruskal-Wallis test. As a result, it find that there were significant differences among the three groups only "men and women changing rooms and showers" (p=0.049) and "with staff restrooms" (p=0.033). The remaining 43 opinions were all consistent. The verification results of K-W are shown in Table 4. Finally, because the experts agree proportion is too low (first round, P=0.2) about the family area is set up in the ward, this study delete the 4 important score items in the second round. The contents are: provided with the accompanying beds, TVs, clothing cabinets, tables and chairs, and even computer networks in ICU wards.

Table 4 K-W test results of the opinions consistency of the three groups of experts

ICU design factors-- "Importance Score Items" in the Delphi questionnaire	χ^2	df	p-value
setting the shower room for man and women separately	6.040	2	0.049＜0.05
This area has a lounge room for the staffs.	6.818	2	0.033＜0.05

4. Conclusion

This study has completed literature collection, questionnaire editing, expert selection, repeated testing and statistical verification analysis. It is expected to propose the recommendations and guidelines for the planning and design of ICU in Taiwan's hospitals. For the selection of planning and design criteria, the more strict consensus standards are adopted among the 43 items that have obtained expert consensus in the research results. One condition to meet the definition of “high consensus” is QD≦0.60. (Yang Yizhen, 1999) Another one to meet "very important" definition is Q1≧4, Q3=5. (Huang Youjie, Luo Shaolin 2001) The strict consensus standard about the select items agreement ratio is P≧0.75. (Murry and Hommons,1995) Summing up the statistical results, this study categorizes all items into three spindles and 25 guidelines. The three spindles are "Enhanced Infection Control", "Enhanced Care Efficiency" and "Appropriate Environmental Design" .According to these three views, the detail guideline content are summarized in Table 5 "Taiwan Intensive Care Unit Planning and Design Guidelines".

In addition to the results of the research on Taiwan's local experts, this study also found that there are two very different design ideas between Taiwan and foreign design trends,. The two important differences are: single ward design and family area design. In this study, the experts considering the limited ICU area in Taiwan, most of them choose a semi-open type of bilateral compartments for each bed. (P value is 55.56%) On the literature and the winning cases, the design trend in the world is a closed single-person wards conducted with a full perspective glass ward door. The main consideration is reducing nosocomial infections. (Teltsch et al, 2011) (Levin et al, 2011) However, studies have also suggested that single-person wards do not help with super-bacteria (MRSA) control, and even due to the person's increased hand washing, not the design of a single-person room. (Cepeda et al, 2005). Despite this, the American Institute of Architects still lists the ICU single ward as a design guide. The French government also requires that all new ICUs in the hospital in the next 20 years must be single-person wards.

Secondly, the experts of this study don’t agree the family stay in ICU ward based on the infection considerations.(The P value of the disapprover is 88.24%) However, the “Hospice Palliative Medical Guidelines” proposed by SCCM and ACCC in the United States and the “Environmental Design” of the family area planned by Mahbub Rashid (2010) support the treatment that are considered to be family decision-making. Therefore, in the best ICU design case selected by AIA in the United States from 1993 to 2012, the proportion of family members in the ward has increased from 12.33% in the previous decade to 70 in the next decade.

Table 5 Taiwan Intensive Care Unit Planning and Design Guidelines

strengthening infection control	Choosing a new address for new construction will be better than renovated
	Sensory hazard assessment is important for new or renovated
	Each sink should be located at the entrance of the ward or at the end of the bed
Improving care efficiency	**The integral design:** single specialist property ward planning to improve safety, quality and efficiency patient care vision, medical staff care line, the optimal size of a unit: 10-19 beds, the optimal configuration of the ward is "racetrack"
	The ward design： the bedside of the bed should be at least 60 cm away from the wall ,the bed end should be at least 150 cm away from the wall, 150 cm on the

	rotating side of both sides, and 120 cm on the non-rotating side. the cantilever medical column has higher accessibility and elasticity than the bedside embedded medical gas cabinet. The columns should have architectural considerations. Each bed should have a ringing bell (calling bell), The living system should have an alarm warning link to the nursing station. Each bed is a separate compartment and the observation station is optimally designed as a "4-bed module". Nursing station should be decentralized design.
	The support service area design： Support service area should be the central nursing station plus observation station, the space should be dispersed to improve care efficiency
appropriate environmental design	**The integral design:** Each unit should have natural lighting and window view
	The ward design： an office for leader, an area for instrument and a multi-purpose room for education training and conference, and a lounge room for dining and rest.
	The support service area design： The family waiting area is outside of ICU, including a toilet and a disease interpretation room.

Supplementary Note 1: The ward of the "racetrack configuration" is mainly centered on the nursing station and the observation station surround the nursing station just as figure 1.

Supplementary Note 2: "4-bed module" refers to the design of the "4 beds, observation stations for 2 nursing staff" based on the care of the manpower just as Figure 2.

Figure 1 The racetrack configuration of the ICU layout by James WP and Tatton Brown W.

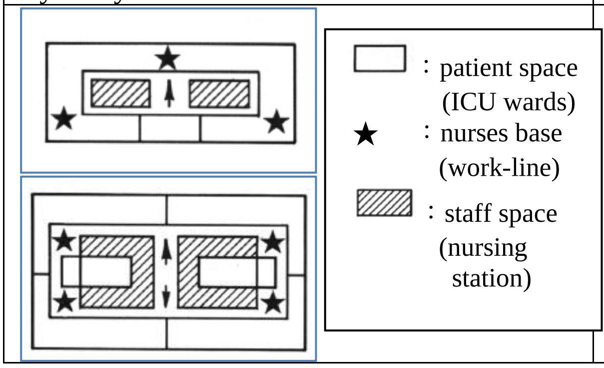
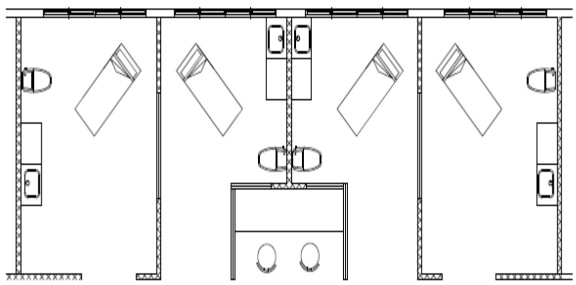


Figure 2 Optimal design module for the nursing staff observation station



This study has the following contributions to the empirical research of hospital ICU design planning: First, for the design of ICU provides an expert structural communication results and the comparison of domestic and international design opinions and trends. In this Delphi decision-making model, research analysis hope to reduce the futile discussion and revision design of the team. Second, this study compared with foreign design trends and viewpoints provides an important reference for the design ideas and a feedback for the experts. Third, the study concludes with recommendations for design planning guidelines. This result is a very specific improvement for setting standards in Taiwan. Finally, the research will investigate the current situation of more than 7,000 ICU beds in Taiwan to compare the similarities and differences with the design criteria proposed in this study in the future. In the future, we can conduct further evidence-based research for these specific design criteria, and proceed the excellent design case competition to advance the level of ICU design.

References

G. Ristagno and M. H. Weil (2009). History of Critical Care MedicineHistory of Critical Care Medicine: the Past, the Present and the Future. Weil Institute of Critical Care Medicine, Rancho Mirage,CA,USA

Neil A. Halpern(2014). Innovative Design for the Smart ICU. CHEST 2014；145(2): 399-403

Jones H. and Twiss B.C.(1978) Forecasting Technology for Planning Decision. New York: Petrocelli Books.

Reza K. and Vassilis S. M.(1988) Delphi hierarchy process(DHP): A methodology for setting derived from the Delphi method and Analytical Hierarchy Process. *European Journal of Operational Research*,No37, 347-354

Andreas Valentin and Ferdinande (2011). Recommendation on basic requirements for ICU: structural and organizational aspect. *Intensive Care Med*(2011)37:1575-1587

Anne, E., Neimeyer, G. J., Pedersen, P.B.(1994). The Delphi technique: a methodological discussion. *Journal of Advances Nursing*, 19, 180-186

McKenna, H.(1994). The Delphi technique: a worthwhile approach for nursing? *Journal of Advances Nursing*, 19(6), 1221-1225

Murry, J. W. and Hammons,J. O.(1993). Delphi : A versatile methodology for conducting qualitative research. *The Review of Higher Education*, 18(4),423-436

Y. J.Huang, S. L. Luo (2001). The Application of Fuzzy Delphi Method in Forestry Administrative Management--A Study Based on the Enterprise Spirit Index of Forest Service Bureau example. *Forestry Research Quarterly*, 23(4):57-72

Y. Z. Yang (1999). Capacity Requirements and Program Design Principles for the Dissemination of Science and Technology Talents: Revised Dephi Research. *Jiaotong University Master Thesis*.

G. Z. Li , Z. Y. Gao , J. X. Lai (1999). Study on the Management of Urban Forest in the Suburbs of Taipei City Chinese Journal of Forestry Sciences, 31(4): 387-404

Mead, D. M.(1992). Innovations in Nursing Care, the Development of Primary Nursing in Wales Unpublish Report. Department of Health, London.

McKenna, H.(1994). The Delphi technique: a worthwhile approach for nursing? *Journal of Advances Nursing*, 19(6), 1221-1225

Teltsch DY, Hanley J, Loo V, Goldberg P, Gursahaney A, Buckeridge DL: Infection acquisition following Intensive care unit room privatization. *Arch Intern Med* 2011,171:32-38

Phillip D Levin, Mila Golovanevski , Allon E Moses, Charles L Sprung and Shmuel Benenson(2011). Im- proved ICU design reduces acquisition of antibiotic-reistant bacteria: a quasi-experimental observational study. *Critical Care* 2011,15:R211. *http://ccforum.com/content/15/5/R211*

Cepeda Ja, Whitehouse T, Cooper B, Hails J, Jones K, Kwaku F, Taylor L, Hayman S, Cookson B, Shaw S, Kibber C, Singer M, Bellingan G, Wilson AP: Isolation of patients in single rooms or cohorts to reduce spread of MRSA in intensive care units prospective two-centre study. Lancet 2005,365:295-304

Parametric Modelling and Structural Optimisation Framework for Early Design Exploration of Tall Buildings

C.L. Wong, Vincent J.L. Gan, K.T. Tse, Irene M.C. Lo, Jack C.P. Cheng, C.M. Chan*,
Dept. of Civil and Environmental Engineering, The Hong Kong
University of Science and Technology (HKUST), HK
* email: cecmchan@ust.hk

Abstract

The increasing complexity of modern tall buildings has raised the importance of close collaboration between architectural and engineering disciplines in the design. However, the first major task in conventional building design is to establish the preliminary shape and architectural appearance, considering the functionality and architectural aesthetics. The structural system is then developed for providing the skeleton of the building, taking account of the safety and stability of the structure. The structural aspect is commonly not considered in the architectural planning stage, while the influence of the architectural design to the structural performance is often overlooked. Therefore, this paper presents a parametric modelling-based optimisation framework for the synthesized architectural-structural design exploration of high-rise buildings at early stages. The proposed framework embeds the parametric modelling technique in the optimisation process. First, the architectural envelop of the building is parametrised by defining the shape variables, which represent the geometric entities, to provide a numerical representation for shape variations. Provided the pre-defined building shape, the design variables for topological arrangement of the building structure is defined by identifying the topological variables. By varying the shape and topology variables, the structural performance of design candidates with different architectural and structural attributes can be evaluated, and the fittest design options can provide recommendations in the preliminary design process and guide the final design scheme decision. A case study demonstrates how the proposed platform can be applied as a decision-support system in the early building design stage and shows the influence of changes in building shape and structural topology to the structural efficiency.

Keywords: Architectural design, High-rise buildings, Optimality criteria, Parametric modelling, Structural optimisation

1. Introduction

Modern tall buildings have become taller and more complex thanks to the advance in construction technology. The increasing complexity of modern architecture has created challenges and difficulties in the design process and has raised the importance of close collaboration between the architectural and engineering disciplines. However, these two disciplines are usually separated in conventional design process and lack interactive coordination in the early design phases. The architects firstly establish the preliminary building shape and layout for satisfying the functional requirements and adding aesthetic value. The structural engineers then develop the structural system for providing the skeleton of the building, considering the safety and the stability of the structure. Commonly, structural considerations are ignored in the architectural planning stage and the influence of the building shape to the structural performance is often overlooked. It is possible that the architects invent the building envelop which is structurally inefficient or even infeasible to be built (Macdonald, 2018). In such cases, the architects and engineers have to work collaboratively and come up with a feasible design, while maintaining the functionality, aesthetics and the structural integrity of the building. In order to facilitate the architectural-structural collaboration, a synthesised design framework is needed for modern tall building design.

Many researchers have proposed design frameworks with the use of parametric modelling for providing solutions to the architectural and structural design synthesis. Park, Elnimeiri, Sharpe and Krawczyk (2004) proposed an interactive design process framework, taking client's requirements, architectural and structural design criteria into consideration. On top of the framework, this study also provided a geometry generation and exploration method, which allows the architects to create unique and distinctive building shapes in a systematic manner and facilitates the generation of the structural model from the architectural model. Another study also presented a framework based on geometric modelling, the hierarchical process model and the integrated architectural-structural representation model for facilitating interactive collaborations (Mora, Bédard, & Rivard, 2008). A synthesised performance-based design approach was proposed for early form design of tall buildings, with the integration the architectural parametric modelling tool and structural analysis tool. (Almusharaf & Elnimeiri, 2010; Elnimeiri & Almusharaf, 2010). The integration of the tools enables structural performance evaluations in the architectural design stage, which in turn can assist the architects to improve the design of the building. Some researchers and practitioners focused on practical applications of the architectural and structural synergy. Holzer, Hough and Burry (2007; 2007) studied interconnectivity of building design software across the two disciplines and developed customised tools for the collaborative process and interdisciplinary decision support. Another stream of researches focused more on the design optimisation on top of the architectural-structural synthesis. Dominik, Jiwu, Mik and Mark (2005) developed a combined approach for architectural form design, using parametric design and evolutionary optimisation techniques, in order to identify appropriate building forms with efficient structural systems. Other researches applied structural topology optimisation techniques for achieving structural efficiency optimality, while maintaining the aesthetics and functionality of the building (Beghini, Beghini, Katz, Baker, & Paulino, 2014; Kingman, Tsavdaridis, & Toropov, 2014; Kingman, Tsavdaridis, & Toropov, 2015). The possibilities of integrating automatic computational techniques of topology optimisation were also investigated for enhancing the computer aided design process (Kazakis, Kanellopoulos, Sotiropoulos, & Lagaros, 2017).

Although some successes in the synergy between architectural and structural design have been demonstrated in the previous studies, the combined influences of the building shape and structural topology arrangement to the structural efficiency were not fully explored. Without a robust hybridised structural topology and member sizing optimisation technique, an accurate structural efficiency assessment could not be conducted comprehensively. Therefore, this paper aims to develop a parametric modelling and structural optimisation framework for providing a more robust structural performance assessment at the early stages of the synthesised architectural-structural design exploration of high-rise buildings. On the other hand, the recent advancement in parametric designing and building modelling tools fosters the development of holistic multidisciplinary design approaches. This study attempts to leverage the state-of-the-art parametric modelling tools for promoting a better architectural-structural synthesis. In this parametric optimisation framework, the architectural form of the building is parametrically represented by defining the shape variables and mathematical functions for generating the geometric entities. The design variables for topological arrangement of the structure are then defined by identifying the topological variables of the structural system. The use of numerical variables and mathematical functions can provide an efficient manner for varying the architectural form and the structural topology of the building. Design candidates with different architectural and structural attributes can be generated by the varying of the shape and topology variables. Another advantage of using parametric representation is the ease of architectural and structural model generation. The parametric variables and functions enable that the models can be generated programmatically, facilitating the structural performance evaluation process for providing design recommendations. This work presents a parametric geometric representation of tall buildings for providing a more generalised model generation method and incorporates a robust structural optimisation technique for more accurate performance evaluation in the early design process.

2. Methodology

2.1. Parametric Optimisation Framework

This section presents the parametric structural optimisation framework for identifying desirable architectural form design with an efficient structural system in the early stages. As shown in *Figure 1*, the purposed framework begins with the design inputs, which there are three main types of inputs: site environment, design regulations and design preference. The framework takes the site condition into account in order to exclude infeasible design candidates in the design process and ensure the validity of the solutions. For example, the development of the building must not exceed the site boundary, and the building height must adhere to the height restriction of the region. With the provided design input, the process proceeds to the architectural form design. First, the shape design parameters, which define the form of the building, are identified by the architects, based on the site condition and designer preferences. The base plan shape and the vertical form of the building are then generated according to the shape parameters. The details of the shape parameters are explained in section 2.2. With the defined geometric information, the architectural model is generated in the building modelling software with parametric design tools. The structural engineers then identify the possible type of structural system and the corresponding structural topology parameters. The details of the structural topology parameters are explained in section 2.3. The structural system of the building is then established accordingly, and the structural analysis model is generated for performance evaluation, followed by structural topology and member sizing optimisation. The building shape can also be altered for improving the structural efficiency in the iterative design process, and the structural design would adapt to the new building form. The influences of the building shape and the topology arrangement to the structural performance is analysed throughout the process, which provide guidance to the architects and engineers for improving the design. After several architectural and structural design cycles, the design team identifies the final design scheme, including the building shape, structural system and preliminary structural member sizes, as the output of this framework.

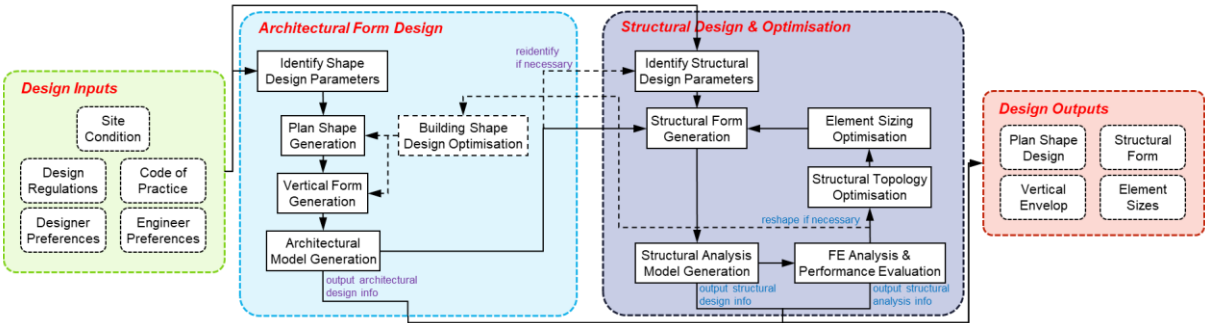
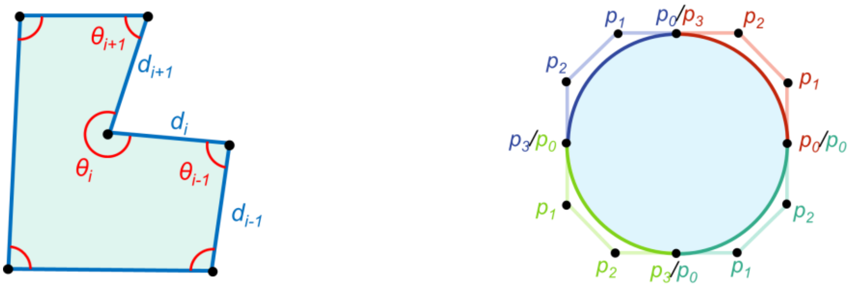


Figure 1: Proposed parametric structural optimisation framework

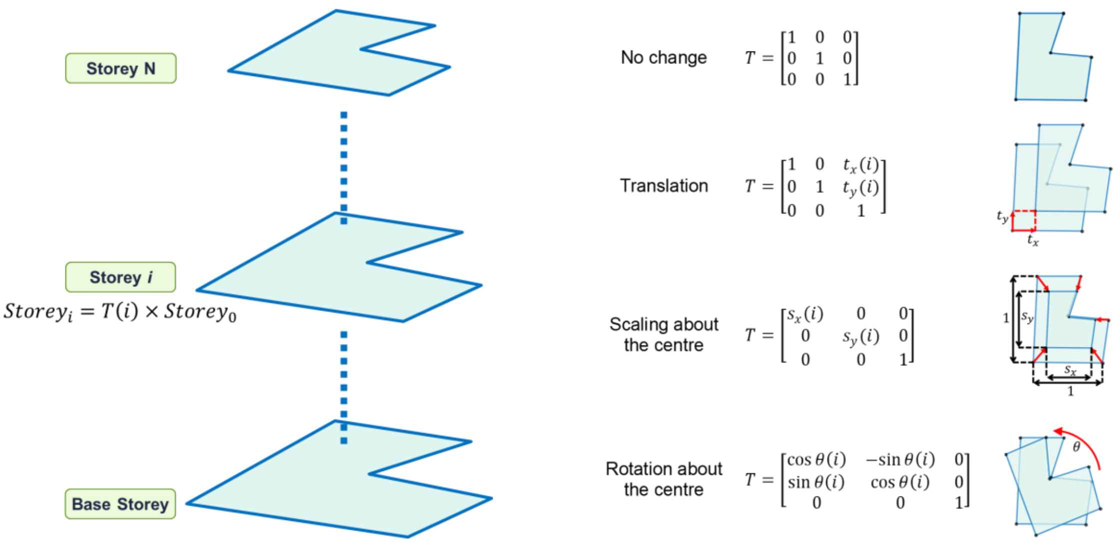
2.2. Building Shape Parameterisation

The concept of parameterising the building shape is to represent the geometry information of the building by using a set of variables and mathematical functions and provide a simple and generic method for generating complex and irregular building forms. The parametric representation of building shapes can be divided into two main components, the horizontal and vertical component. The horizontal component represents the base floor plan shape of a building; and the vertical component means the vertical envelop of a building. The base floor plan shape is defined by the architects using the parametric representation of geometry. For the plan shape with straight edges, like the “L-shape” floor plan in *Figure 2(a)*, the outline of the shape can be represented as a set of edge lengths and the angles between the edges as the parameters. *Figure 2(b)* shows another example of a circular base plan shape with curved edges, which the outline of the shape is represented by a collection of Bezier curves, and the shape parameters are the controlling points of the curves. Not only limited to the parameterisation methods shown in *Figure 2*, other representations can also be applicable, as long as the building plan shape can be depicted by the parameters.



(a) Representation for straight lines *(b) Representation for curves using Bezier curves*

Figure 2: Parametric representation for base plan shapes of buildings



(a) Vertical relationship representation *(b) Vertical transformation operations*

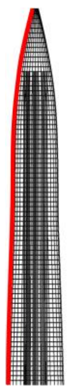
Figure 3: Parametric representation for vertical envelop of buildings

With the parameters for the base plan shape, the vertical form and the overall envelop of the building are then parametrically defined by a set of mathematical functions. The geometry of the plan shapes of the levels above the base level are represented by the transformation function with reference to the base plan shape (as shown in *Figure 3*). The "no change" transformation with the identity matrix can represent the prismatic building with constant floor plan shapes along the building height, like the original world trade centre in New York. The inclined shapes of the world-famous twin skyscrapers, the Gate of Europe, in Madrid can be represented by the translation function. The scaling transformation can generate the setback of the plan shape commonly found in tall buildings, which the floor plans getting smaller along the building height. The twist towers, Cayan Tower in Dubai and Turning Torso in Malmö can also be modelled by using rotation transformation to resemble the twisting effects of these distinctive shapes. Moreover, the different transformations of the building shape can be used combinedly, providing flexibility and more variations for modelling the vertical form of the building.

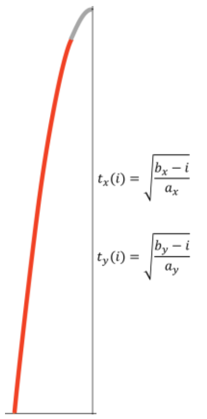
The usage of the transformation functions can provide a simple representation for the envelop of high-rise buildings. Regardless of the height of the building, number of the parameters or design variables for the vertical shape of the building is maintained in a small size, resulting in a scalable design problem. However, for buildings with discontinuity in the plan shape along the building height, like the

Bank of China Tower in Hong Kong, the vertical shapes cannot be simply represented by the continuous transformation functions. Multiple sets of the shape parameters are required for separate parts of the buildings. The benefit of parameterisation is less significant in such cases.

As shown in *Figure 4(a)*, the building with a nose-cone vertical form has the floor plan shrinking in size along the building height. This nonlinear shrinkage of building plan can be represented by the scaling transformation function, where the scaling ratio is also a function with respect to the storey number or height. *Figure 4(b)* shows an example of the square root function for the scaling ratio in x and y directions. a_x, a_y, b_x and b_y are the parameters of the functions defined by the designers. The parameters can be adjusted according to the architects' preference to control shape of the building envelop. The functions are not only limited to be quadratic; other functions, like trigonometric, exponential, reciprocal or polynomial functions, can also be applied. Similarly, the rotating angle θ of rotation transformation is a mathematical function in terms of the storey level as well. An example of a building with a linear rotation of the floor plans, with an increasing rotating angle θ of 2° for every storey, is shown in *Figure 4(c)*.



(a)Vertical variation of the building envelop



(b) Function of the scaling factor w.r.t the storey level

(c) Building model of the rotational transformation

Figure 4: Parametric function for representing the vertical variation (i.e. scaling and rotation) of the plan shape

2.3. Structural Topology Parameterisation

After having defined building shape, the structural engineers identify the best suitable structural systems (e.g. outrigger-braced, tubular system). Each structural system has a particular set of topology parameters. For instance, an outrigger-braced structure with three locations of outrigger trusses (as shown in *Figure 5(a)*) has a set of three variables representing the storey levels of the trusses and a set of variables indicating the column spacing of the perimeter frame. *Figure* 5*(b)* and *(c)* shows two examples of the variations of the structural topology variables for an outrigger-braced structure. The design in *Figure 5(b)* has a wider column grid spacing, and the design in *Figure 5(c)*) places the bottom outrigger truss at a much lower level. The structural model is then generated by parametric modelling tools according to the defined topology parameters for the structural performance evaluation.

(a) Original design (b) Design variation in column grid spacing (c) Design variation in outrigger truss level

Figure 5: Illustrations of variations of the structural topology variables

2.4. Member Sizing Optimisation

To conduct an accurate structural performance evaluation for the design candidates, varying from the shape of the building and the topology arrangement of structural elements, structural member sizing optimisation is applied in the structural design of each individual candidates. A robust optimality criteria method (C.-M. Chan, Grierson, & Sherbourne, 1995; C. M. Chan, 2001) is adopted for minimising the total amount of structural materials required in the building while satisfying member strength requirements and the lateral drift limits under wind loads. The design with the given building shape and structural topology, expressed in terms of the shape and topology variables, is transferred to structural analysis model for structural performance evaluation and member sizing optimisation. Following the sizing optimisation, the structural material demand for the design candidate is quantified and structural efficiency comparison between different designs is carried afterwards.

3. Result and Discussion

This section presents an illustrative example of applying the propose framework. Two buildings with peculiar forms in China, the China Resources Headquarters and the CITIC Tower (aka China Zun) are as the reference buildings in the study, as shown in *Figure 6*.

(a) *(b)*

Figure 6: Reference buildings: (a) China Resources Headquarters, (b) China Zun

3.1. Building Shape Design

With the insights about building shapes from the two reference buildings, 6 different building form were generated as the demonstrative examples, as shown as *Figure 7*. They are all 400 m tall and having around 240,000 m^2 of the total floor area for providing the same level of functionality and serviceability. The first 3 designs, *(a)-(c)*, with the circular plan shapes are mimicking the China Resource Headquarters, and another 3 designs, *(d)-(f)*, are resembling the round square plan shape of the China Zun. The illustrative example not only makes reference to the plan shapes, the vertical forms of the two special buildings are also taken into consideration, such as the convex, “bullet-like” shape is adopted in design *(a)* and *(d)*, and design *(c)* and *(f)* replicate the concave, “vase-like” shape. In addition, two buildings with linear vertical outline were modelled for a more comprehensive analysis of the influence of building shapes to the structural efficiency. To conduct the structural performance analysis, the structural models for the 6 shapes are generated, and the structural systems are fitted within the building envelops accordingly. In this illustrative example, the tubular structural system is used for all the shapes, since this system can adaptively fit for the irregular geometry of the buildings. Only the elements contributing to the lateral stability systems are designed because the ability of resisting wind loads is a critical criterion for tall building design.

(a) (b) (c) (d) (e) (f)

Figure 7: Variations of the building shapes: circular plan shape with (a) convex outline, (b) linear outline, (c) concave outline and rounded square plan shape with (d) convex outline, (e) linear outline, (f) concave outline

The lateral stability systems for all the building shapes were design according to the same code of practice and under the same loading conditions. The member sizes were optimised for achieving the minimum structural material cost while the top deflections of the buildings are controlled within the limits. *Figure 8* shows the optimised material cost for each design candidate, and the vertical axis represents the structural material cost required in the lateral stability system, i.e. the total material cost of the perimeter steel frame and the interior concrete core wall. The design *(b)* with a circular plan shape and a linear vertical outline is the most cost-effective design while satisfying the same structural requirements and functional demands. Comparing to the buildings with other vertical outline, this design has a vertical shape with the floor plans decreasing in size along the building height, whereas the convex and concave shapes have larger building widths in the middle or the upper part of the buildings. This feature can significantly reduce the wind load on the building due to the smaller frontal projected area, and thus less structural materials are required for maintaining the allowable amount of lateral deflection when withstanding the overturning moment. This similar observation can also be found in the rounded-square buildings (i.e. design *(d)-(f)*). Even though design *(b)* and *(e)* also have the linear vertical profile, the former has slightly better structural efficiency, due to the more aerodynamically streamlined circular shape resulting in a smaller amount of wind loads than the rounded square building. In this example, only the code-stipulated wind loads were used in the analysis, computational fluid dynamic analysis tools or wind tunnel testing data can be used for a more accurate and sophisticated structural performance assessment, especially for the buildings with irregular shapes.

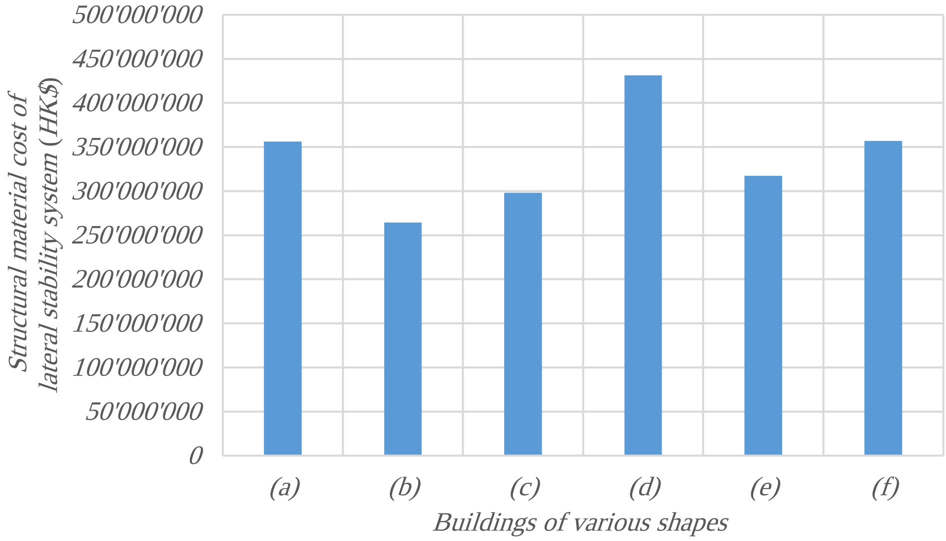


Figure 8: Optimised structural material cost for the different building shapes

3.2. Structural Topology Design

The building shape design candidate with the best structural efficiency (i.e. design *(b)*) is adopted and the design process then proceeds to the structural topology design. In this illustrative example, the tubular structural system is used in this circular building. The structural system consists of a core wall part and a perimeter frame of beams and closely spaced columns. The number of perimeter columns is the only topology variable in this example. 8 cases of different number of columns were investigated, as shown in *Figure 9*, ranging from 34 columns to 48 columns. The average column spacing is about 3-6 meters, which is within the optimal range of column spacing for the tubular system, and the columns are separated reasonably wide enough for practical reasons and constructability concerns.

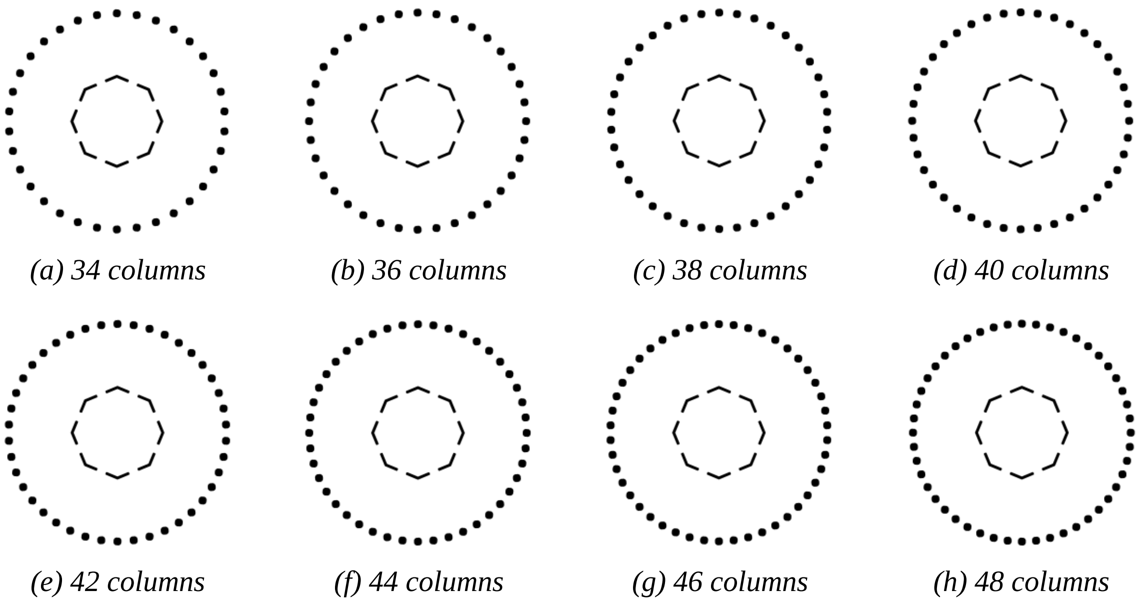


Figure 9: Variations of the structural topology variable (i.e. no. of perimeter columns) for the example building

The member sizing optimisation process was then undertaken for the 8 design candidates with different numbers of perimeter columns. The optimised structural material consumptions for each individual building are shown in *Figure 10*. The structural material weight of the vertical axis in the figure represents the total weight of the construction material required in the lateral stability system and includes the material of the perimeter steel frame and the interior concrete core wall. It shows the trend that the buildings with closer perimeter column spacing require less structural materials for achieving the same structural performance. The design with 48 columns can save about 16% of structural materials, comparing to the design with 34 columns. Because of the working principle of a tubular structural system in this circular building, the closely spacing column can reduce the shear lag effects of the perimeter beams, which in turn that the beams can be more efficient for carrying loads between the columns. Therefore, the tubular structures with closely spaced perimeter columns can achieve better structural efficiency. In this case, the design with 46 or 48 columns is much preferable and suggested. This part of the example can demonstrate how the proposed framework provides recommendations and suggestion for assisting the structural engineers.

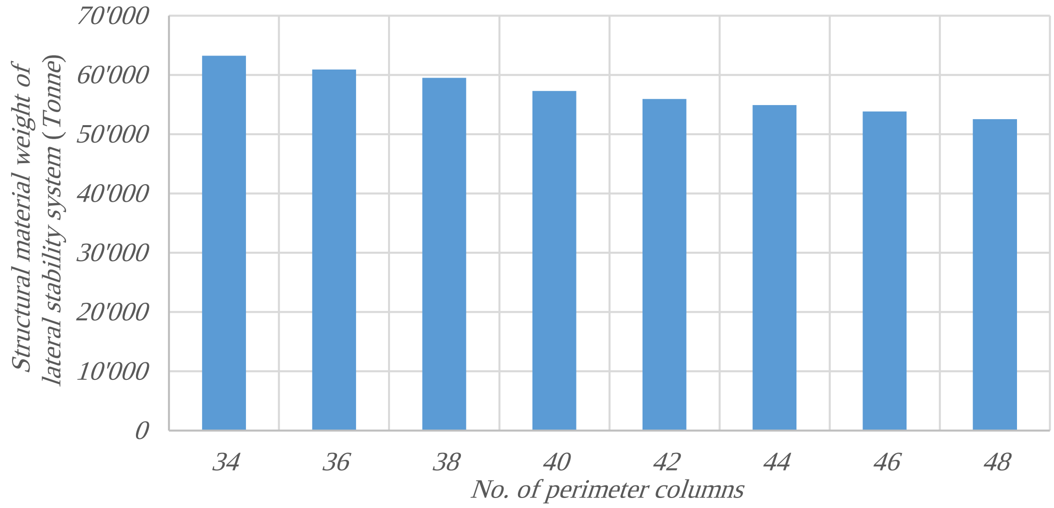


Figure 10: Optimised structural material consumptions for the design candidates with different numbers of perimeter columns

Despite the fact that the design candidates with more columns are preferable from the structural engineering point of view, these design solutions may not be practically and aesthetically desirable for the clients and architects. The closely placed columns would create blockage for sunlight penetrating the indoor environment, which reducing the natural daylight for the building. The design may also affect the aesthetic value of the building, for instance, the densely spaced columns may create an unattractive interior environment. This kind of conflicts requires collaboration of architects and engineers and interactions throughout the design process.

4. Conclusion and Future Work

This paper presented a parametric design and structural optimisation framework for early design stages of tall buildings. On top of the synergy between architectural and structural discipline, this work introduced a numerical representation method for building shape generation and incorporated a robust structural optimisation technique to accurately evaluate each design candidates. A case study demonstrated how the proposed framework was applied in the early design stage of a tall building which can provide recommendations for architects to improve the design and guide engineers to come up with an efficient structural system design. Even though the work of this paper focused on the early building design phase, the proposed framework can be further extended to later part of the design and provide a base platform for detailed design, for example rebar and steel connection design. These would provide a more holistic tall building design platform for the early to detailed design phases and for system-level to component-level design.

References

Almusharaf, A., & Elnimeiri, M. (2010). A Performance-Based Design Approach for Early Tall Building Form Development. Paper presented at the 5th International Conference of the Arab Society for Computer Aided Architectural Design, Fez, Morocco.

Beghini, L. L., Beghini, A., Katz, N., Baker, W. F., & Paulino, G. H. (2014). Connecting architecture and engineering through structural topology optimization. Engineering Structures, 59, 716-726. doi:10.1016/j.engstruct.2013.10.032

Chan, C.-M., Grierson, D. E., & Sherbourne, A. N. (1995). Automatic Optimal Design of Tall Steel Building Frameworks. 121(5), 838-847. doi:10.1061/(ASCE)0733-9445(1995)121:5(838)

Chan, C. M. (2001). Optimal lateral stiffness design of tall buildings of mixed steel and concrete construction. Structural Design of Tall Buildings, 10(3), 155-177. doi:10.1002/tal.170

Dominik, H., Jiwu, T., Mik, X., & Mark, B. (2005). Design Using Evolutionary Optimisation and Associative Geometry. Paper presented at the 11th International CAADFutures Conference, Vienna, Austria.

Elnimeiri, M., & Almusharaf, A. (2010). Structure and architectural form of tall buildings. Paper presented at the International Conference on Sustainable Building Asia, Seoul, Korea.

Holzer, D., Hough, R., & Mark, B. (2007). Parametric Design and Structural Optimisation for Early Design Exploration. International Journal of Architectural Computing, 5(4).

Holzer, D., Mark, B., & Hough, R. (2007). Linking Parametric Design and Structural Analysis to Foster Transdisciplinary Design Collaboration. Paper presented at the 12th International Conference on Computer-Aided Architectural Design Research in Asia, Nanjing, China.

Kazakis, G., Kanellopoulos, I., Sotiropoulos, S., & Lagaros, N. D. (2017). Topology optimization aided structural design: Interpretation, computational aspects and 3D printing. Heliyon, 3(10), e00431. doi:doi.org/10.1016/j.heliyon.2017.e00431

Kingman, J. J., Tsavdaridis, K. D., & Toropov, V. V. (2014). Applications of topology optimization in structural engineering. Paper presented at the Civil Engineering for Sustainability and Resilience International Conference (CESARE).

Kingman, J. J., Tsavdaridis, K. D., & Toropov, V. V. (2015). Applications of topology optimization in structural engineering: High-rise buildings and steel components. Jordan Journal of Civil Engineering, 159(3097), 1-23.

Macdonald, A. J. (2018). Structure and architecture (Third ed.). London: Routledge.

Mora, R., Bédard, C., & Rivard, H. (2008). A geometric modelling framework for conceptual structural design from early digital architectural models. Advanced Engineering Informatics, 22(2), 254-270. doi:10.1016/j.aei.2007.03.003

Park, S. M., Elnimeiri, M., Sharpe, D. C., & Krawczyk, R. J. (2004). Tall building form generation by parametric design process. Paper presented at the CTBUH 2004 Seoul Conference, Seoul, Korea.

Determinants of users' acceptance of a computer-based system

Elaheh Jalilzadehazhari[1*], Peter Johansson[2], Jimmy Johansson[3]

[1,3] Department of Forestry and Wood Technology, Linnaeus University, Växjö 35195, Sweden

[2] Department of Construction Engineering and Lighting Science, Jönköping 551 11, Sweden

* email: elaheh.jalilzadehazhari@lnu.se

Abstract

Sweden has an ambitious target to attain 50% more efficient energy use by 2030. Improving the energy performance of buildings provides a great opportunity to achieve the above-mentioned target. At this point, windows play a substantial role in improving indoor environmental quality and reducing energy consumption and cost. A computer-based system was therefore developed, which allows selecting a suitable window design. The computer-based system was intended to be used in a large-sized window and door manufacturing company in Sweden. However, the benefits of implementing the computer-based system cannot be realized until users accept using it. Former literature employed the technology acceptance model to investigate the influence of external variables on cognitive beliefs and trace their effects on users' intention and actual system use. A successful application of TAM relies on the specification of the external variable. Accordingly, this paper conducted a systematic literature review to determine the external variable, affecting users' acceptance, thereby extended TAM. The analyses of results showed that organizational, individual, technological and environmental characteristics were the most influential external variables when investigating determinants of users' acceptance toward a computer-based system. Organizational characteristics contained mainly top management support, training, organizational culture, and organizational size, while individual characteristics embraced users' previous knowledge and experience. Technological characteristics comprised information quality and system quality, meanwhile environmental characteristics included fulfillment of regulations and competitiveness. The extended TAM overcomes limitations attributed to the unified theory of acceptance and use of technology model since it considers attitude as direct determinants of intentions. In addition, the extended TAM is advantageous when compared with technology, organization, environment framework, because it has clear constructs, which allows tracing the influence of external variables on cognitive beliefs, and thereby their effects on users' intention and actual system use. The extended TAM will be used to investigate determinants of users' acceptance of the computer-based system in the manufacturing company in Sweden and compare the effect of external variables on users' acceptance.

Keywords: Technology acceptance model, computer-based system, perceived usefulness, perceived ease of use

1. Introduction

The Paris agreement commits parties to the United Nations Framework Convention on Climate Change to advance actions required for cutting greenhouse gas emissions, thereby mitigating climate changes (United Nations, 2019). In addition, the European Performance of Building Directive obliged European countries to ensure zero energy codes and minimum indoor comfort thresholds when constructing new buildings (EPBD 2010). An ambitious target was therefore set in Sweden, which binds the country to attain 50% more efficient energy use by 2030 (Goverment Offices of Sweden, 2019). Although several efforts have undertaken to fulfill the abovementioned target, the total energy consumption within the building and service sector has mainly remained unchanged (Swedish Energy Agency, 2019). This occurs due to the existence of a strategic conflict: whether to enhance the efficiency of supply-side technologies and exploit renewable energy resources or improve the efficiency of demand-side services and technologies (Lundström, 2016). The abovementioned conflict is more illustrated in countries such as Sweden, where the biomass-based district heating system makes up the greatest share in supporting the heating demand in building and service sector (Swedish Energy Agency, 2019). Substituting the biomass-based district heating system is a complex matter due to a high share of secondary energy resources such as waste materials and forestry residuals and cogeneration of electricity and heat in several power plants (Lundström, 2016). The complexity of substituting district heating system shifts focuses on improving the efficiency of demand-side services and technologies for reducing the total energy demand (Hee et al., 2015). According to Hee et al. (2015) and Jalilzadehazhari, Johansson, Johansson, and Mahapatra (2018), the energy performance of buildings and the state of indoor environmental quality depend on building envelopes particularly windows. However, selecting a suitable window is a complex task due to three main difficulties: i) existence of conflicts between visual comfort, thermal comfort, energy consumption and life-cycle cost, ii) availability of various window designs with different sizes, positions, glazing systems, and forms, and iii) the need for considering all criteria which have effect on visual comfort, thermal comfort, energy consumption, and life-cycle cost when selecting windows (Jalilzadehazhari, Johansson, & Mahapatra, 2018).

To overcome the abovementioned difficulties, Jalilzadehazhari, Johansson, Johansson, et al. (2018) introduced a decision-making framework, which allows selecting a window design based on the trade-off between visual comfort, thermal comfort, energy consumption, and life-cycle cost. The decision-making framework is an interactive computer-based system, which utilizes a simulation tool and an optimization platform to select a trade-off window design (Jalilzadehazhari, Johansson, Johansson, et al., 2018). The computer-based system was intended to be used in a large-sized window and door manufacturing company[1] in Sweden to help either private clients or architects and designer in selecting a trade-off window design. Although, the strength of the decision-making framework in solving complex and conflicting tasks was tested and found appreciated (Jalilzadehazhari, Johansson, & Mahapatra, 2018) the complexity of the computer-based system can perceive as a barrier for its implementation in design practices (Lu et al., 2014). Accordingly, benefits expected from implementing the computer-based system cannot be realized unless users[2] accept using it in design practices (Saadé & Kira, 2007). According to Park, Son, and Kim (2012), the reason for failure in the deployment of computer-based systems is not that they failed to fulfill as expected, but rather that users refused to use them.

Former studies investigate the determinants of user acceptance of a computer-based system using the technology acceptance (TAM) model. TAM allows tracing the influence of external variables on cognitive beliefs, and thereby their effects on users' intention and actual system use (Venkatesh, Morris, Davis, & Davis, 2003). Although TAM has been widely applied in different fields (Acquah & Oteng, 2018; Lee, Yu, & Jeong, 2013; Son, Lee, Hwang, & Kim, 2014; Usman & Said, 2012), it received criticisms due to confusion over external variables (Gangwar, Date, & Raoot, 2014). Thus, investigating the determinants of users' acceptance of computer-based systems requires exploration of external variables, which affects their actual use. This study conducts a systematic literature review and summarized external variables, affecting users' acceptance towards computer-based systems, thereby extends TAM. The extended version of TAM in this paper will be later used to investigate determinants of users' acceptance of the computer-based system in the manufacturing company in Sweden and compare the effect of external variables on users' acceptance.

[1] The manufacturing company has more than 1000 employees, thereby is considered as a large-sized company (Arnold, 2012)

[2] Shih and Venkatesh (2004) discussed about four typologies of users: intense users, specialized users, non-specialized users, and limited users. Intense users utilize a computer-based system for a significant amount of time to perform a variety of tasks, while specialized users spend much time using the system but for doing limited tasks (Shih & Venkatesh, 2004). Non-specialized users exploit the computer-based system to perform different tasks but for a limited amount of time, but limited users apply the system for a limited variety of use and for a short period of time (Shih & Venkatesh, 2004).

2. Technology acceptance model

The TAM, originally derived from the theory of Reasoned Action and theory of planned behavior, aims to discover users' acceptance related to a board variety of ICT technologies (Lee et al., 2013; Venkatesh et al., 2003). Application of TAM allows one to investigate the influence of external variables on cognitive beliefs and trace their effects on users' intention and actual system use (Figure 1) (Venkatesh & Davis, 1996). Cognitive beliefs within the TAM comprise users' perceived usefulness and perceived ease of use (Venkatesh & Davis, 1996). Perceived usefulness refers to users' beliefs regarding the usefulness of a computer-based system in enhancing their job performance (Venkatesh & Davis, 1996), while perceived ease of use is defined as the degree to which users believe that using the computer-based system is free of effort (Venkatesh & Davis, 1996). One of the main advantages of TAM is its simplicity (To, Lee, & Lam, 2018), accordingly, it allows researchers to extend TAM and test several hypotheses, drawing upon TAM to explain users' acceptance of ICT technologies.

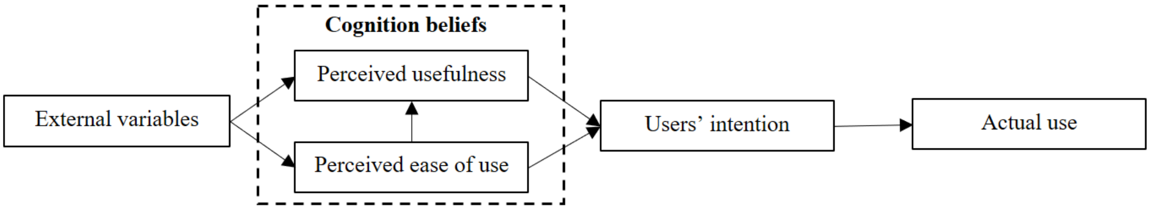


Figure 1: The TAM, proposed by Venkatesh and Davis (1996)

3. Methodology

The search for relevant literature was accomplished in the Scopus database, using six main keywords, including "technology acceptance model", "manufacturing", "architecture", "construction", "ICT" and "computer-based system". The subject area was limited to "business, management and accounting", "engineering", "computer science", "decision science", "energy", "mathematics", "economics, econometrics and finance", "environmental science" and "social sciences". Furthermore, each search term was limited to English language literature, published from 2000 until 2019. The primary search resulted in 146 literature. The abstract of found literature was read and the eligible 49 literature were selected for further review. In addition, relevant literature cited by 49 eligible literature were reviewed to gain in-depth knowledge.

4. Results

Investigated literature considered multiple external variables and analyzed their effects on actual system use. Figure 2 summarized the most influential external variables when investigating determinants of users' acceptance towards computer-based systems, that includes organizational, individual, technological and environmental characteristics. Technological characteristics with a share of 33% were the most studied external variables; following by organizational characteristics with a share of 20%, then individual and environmental characteristics with a similar weight of 12%.

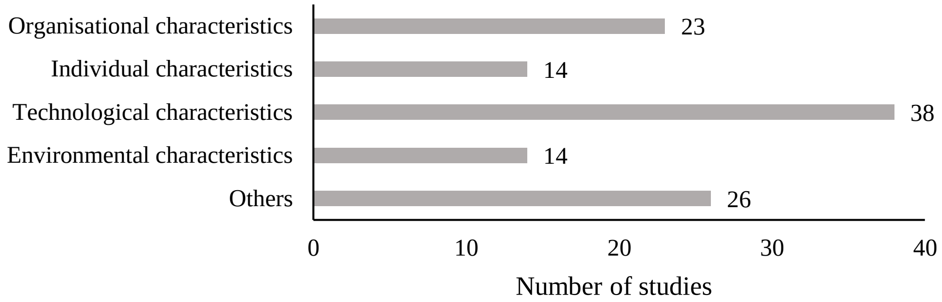


Figure 2: The most influential external variables

4.1. Extended TAM and hypotheses

Organizational characteristics [3] comprised mainly top management support, training, organizational culture, and organizational size (Park et al., 2012; Peansupap & Walker, 2004). Top management support refers to the degree to which the top management comprehend the value of a computer-based system and the domain to which it is exploited in the activities of an organization (Al Haderi, Fareen Abdul Rahim, & Mohammed Bamahros, 2018). Top management support can be considered as one of the most essential factors influencing actual system use (Tatari, Castro-Lacouture, & Skibniewski, 2007) because it is attributed to users' appraisal about top management commitment in allocating resources to support the adoption of a computer-based system (Kamel, 2010). According to Peansupap and Walker (2006), the lack of top management support can evince user resistance to use a new computer-based system. On the contrary, top management commitment in designing a suitable strategy for supporting the acquisition of a computer-based system can reduce users' anxiety and boosts their self-efficacy (Al Haderi et al., 2018). Former literature discussed that top management support is strongly correlated to perceived usefulness and perceived ease of use (Lewis, Agarwal, & Sambamurthy, 2003). The following hypotheses were therefore posited:

Hypothesis 1. Top management support has a significant positive effect on perceived usefulness.
Hypothesis 2. Top management support has a significant positive effect on perceived ease of use.

The training was also concluded as an important factor, which affects perceived usefulness and perceived ease of use (Peansupap & Walker, 2005). Training is an effective way to simplify a computer-based system use in practice, furthermore, it can help users in realizing the usefulness of a computer-based system (Peansupap & Walker, 2005). Training is often influenced by top management support (Tahilramani, 2013) and organizational social context (Tahilramani, 2013). Top management commitment to the training can ensure users' active participation in training, thereby streamlining the use of a computer-based system (Tahilramani, 2013) and improves the effectiveness of the system (Kamel, 2010). Furthermore, the social context within an organization influences the encouragement of training to knowledge acquisition, because it can promote personal developments. Accordingly, the following hypotheses were adopted:

Hypothesis 3. Training has a significant positive effect on perceived usefulness.
Hypothesis 4. Training has a significant positive effect on perceived ease of use.
Organizational culture is mainly defined as an intricate set of assumptions and values (Jones,

[3] Former studies included strategic ICT planning as a significant organizational characteristic, which affects the adoption of a computer-based system in organizations. Strategic ICT planning aligns a computer-based system to organizational objectives (Peansupap & Walker, 2004). Existing of a long-term strategic ICT plan, such as cost reduction strategy and differentiate strategy, can provide competitive advantages to organizations (Peansupap & Walker, 2004). The cost reduction strategy stresses using computer-based systems to improve users' performance and productivity, thereby cutting time and cost, while the differentiated strategy concentrates on using computer-based systems for developing new products, which provides possibilities for new business delivery (Peansupap & Walker, 2004). However, the strategic ICT planning affects organizational decision-making in using computer-based systems (Peansupap & Walker, 2004) rather than users' acceptance, accordingly, it was excluded when extending TAM.

Jimmieson, & Griffiths, 2005), which shape the manner in which organizations carry on their businesses (Mansor, Tayib, & Science, 2010). Values, which are considered as central elements of organizational culture, are employees shared rules and beliefs, that distinguishes an organization from other organizations (Mansor et al., 2010). Hofstede, Neuijen, Ohayv, and Sanders (1990) specified six dimensions to characterize organizational culture, from which three of them were used often when studying users' acceptance of a computer-based system (Ciganke, Mao, & Srite, 2008; Mahomed et al., 2017): Results-oriented vs process-oriented culture, Employee-oriented vs job-oriented culture, and Open-system vs close-system culture. Result-oriented culture concentrates mainly on exploring new ideas and achieving desired results to fulfill organizational objectives, while process-oriented culture promotes risk-avoidance culture among employees with less creativity. According to Ruppel and Harrington (2001), an organization with result-oriented culture improves users' perceived usefulness and perceived ease of use. The following hypotheses were therefore posited:

Hypothesis 5. Result-oriented culture has a significant positive effect on perceived usefulness.
Hypothesis 6. Result-oriented culture has a significant positive effect on perceived ease of use.

An organization with employee-oriented culture shows a great concern about employees' personal needs, in contrast, an organization with job-oriented culture focuses on outputs rather than employees' need. Mahomed et al. (2017) discussed that organizations with employee-oriented culture are more likely to embrace a new computer-based system and give employees opportunities to realize its benefits, thereby improves users' perceived usefulness and perceived ease of use. Accordingly, two further hypotheses were adopted:

Hypothesis 7. Employee-oriented culture has a significant positive effect on perceived usefulness.
Hypothesis 8. Employee-oriented culture has a significant positive effect on perceived ease of use.

Furthermore, an organization with open-system culture welcomes newcomers, where employees have a sense of belonging to the organization, while an organization with closed-system culture is secretive even to its employees (Mahomed et al., 2017). Employees of an organization with open-system culture are willing to share their experiences and aid each other when using a new computer-based system, which can enhance users' perceived usefulness and perceived ease of use (Ciganke et al., 2008). Therefore, the following hypotheses were considered:

Hypothesis 9. Open-system culture has a significant positive effect on perceived usefulness.
Hypothesis 10. Open-system culture has a significant positive effect on perceived ease of use.

Former studies have mainly contradictory attitudes regarding relationships between organizational size and users' acceptance of a computer-based system. For instance, Cho (2007) and Nikas, Poulymenakou, and Kriaris (2007) stated that larger organizations spend additional effort on the effectiveness of a computer-based system, thereby affect perceived usefulness and perceived ease of use. Because larger organizations deal with greater business and operational complexity, furthermore they have more organizational and economic resources (Cho, 2007; Nikas et al., 2007). While Hua (2007) discussed that small and medium-sized organizations have more flexibility, accordingly they more likely to support a new computer-based system and thereby improve users' perceived usefulness and perceived ease of use. The following hypotheses were therefore considered:

Hypothesis 11. Organizational size has a significant positive effect on perceived usefulness.
Hypothesis 12. Organizational size has a significant positive effect on perceived ease of use.

Individual characteristic comprises users' previous knowledge and experience, which refers to the degree whether or not users know how to use a new computer-based system (Lu et al., 2014; Xu & Quaddus, 2005). Lack of knowledge and skill can negatively impact perceived usefulness and perceived ease of use; accordingly, it makes the actual use of a computer-based system a sophisticated matter. The latest statement is more illustrated in small and medium-sized companies since they can be incapable to afford a high-salary position to expert personnel (Lu et al., 2014). Thus, the following hypotheses were posited:

Hypothesis 13 users' previous knowledge and experience have a significant positive effect on perceived usefulness.

Hypothesis 14. Users' previous knowledge and experience have a significant positive effect on perceived ease of use.

Technological characteristics in terms of computer-based system usage include mainly different attributes of information quality and system quality (DeLone, McLean, & out of mind, 1999; Park et al., 2012). Information quality refers mainly to accuracy, reliability, and compatibility of a computer-based system. Former literature has a controversial view when investigating the importance of information quality. Some literature propounded information quality as being important from users' perspective (Mohd, Syed-Mohamad, & Zaini, 2005), while others considered it as being important from vendor's view (Chismar & Wiley-Patton, 2003). The results of previous literature have shown that information quality is significantly correlated to perceived usefulness and perceive ease of use (Chismar & Wiley-Patton, 2003; Lin, 2007; Mohd et al., 2005; Wang, Wang, & Education, 2009). Accordingly, the following hypotheses were considered:

Hypothesis 15. Information quality has a significant positive effect on perceived usefulness.

Hypothesis 16. Information quality has a significant positive effect on perceived ease of use.

System quality stresses simplicity and responsiveness of a computer-based system (Lu et al., 2014; Park et al., 2012; Son et al., 2014). Users' experience in terms of system quality has a significant influence on their perceived usefulness and perceived ease of use (Lin, 2007; Wang et al., 2009), thereby it shapes their intentions in accepting a computer-based system and affects actual use. The following hypotheses were therefore added:

Hypothesis 17. System quality has a significant positive effect on perceived usefulness.

Hypothesis 18. System quality has a significant positive effect on perceived ease of use

Environmental characteristics include mainly governmental regulations, competitiveness (Al-Fahim, Jusoh, & Abideen, 2014; Hameed & Arachchilage, 2017) and market demands (Nikas et al., 2007). The fulfillment of environmental characteristics can positively influence the output quality and results' demonstrability. Output quality refers to the degree to which users believe that a new computer-based system can accomplish required tasks, while result demonstrability is about the tangibility of the results (Gupta, Singh, & Bhaskar, 2016). The results of previous literature have shown environmental characteristics are significantly related to perceived usefulness and perceived ease of use (Akça & Özer, 2016). Thus, the following hypothesis was included:

Hypothesis 19. Governmental regulations and competitive forces have a significant positive effect on perceived usefulness.

Hypothesis 20. Governmental regulations and competitive forces have a significant positive effect on perceived usefulness.

Further hypotheses were posited to explain the relationship between perceived usefulness and perceived ease of use. According to Legris, Ingham, Collerette, and management (2003) and Venkatesh and Davis (2000), a computer-based system is perceived more useful when it is easy for users to utilize it in practice, that explains the effect of perceived ease of use on perceived usefulness. Enhanced perceived usefulness and perceived ease of use can improve user's intention in using a computer-based system, which can later lead to actual system use (Liao et al., 2018; Venkatesh & Davis, 1996). Thus, the following hypotheses were considered:

Hypothesis 21. Perceived usefulness has a significant positive effect on users' intention.

Hypothesis 22. Perceived ease of use has a significant positive effect on users' intention.

Hypothesis 23. Perceived ease of use has a significant positive effect on perceived usefulness.

Hypothesis 24. Users' intention has a significant positive effect on actual use.

Figure 2 illustrates the extended version of TAM, developed to investigate determinants of users' acceptance of a computer-based system. It includes the organizational, technological, individuals and environmental characteristics, and presents how they affect users' perceived usefulness and perceived ease of use, thereby shape the actual use. The arrows show hypothesized relationships in the direction of arrows.

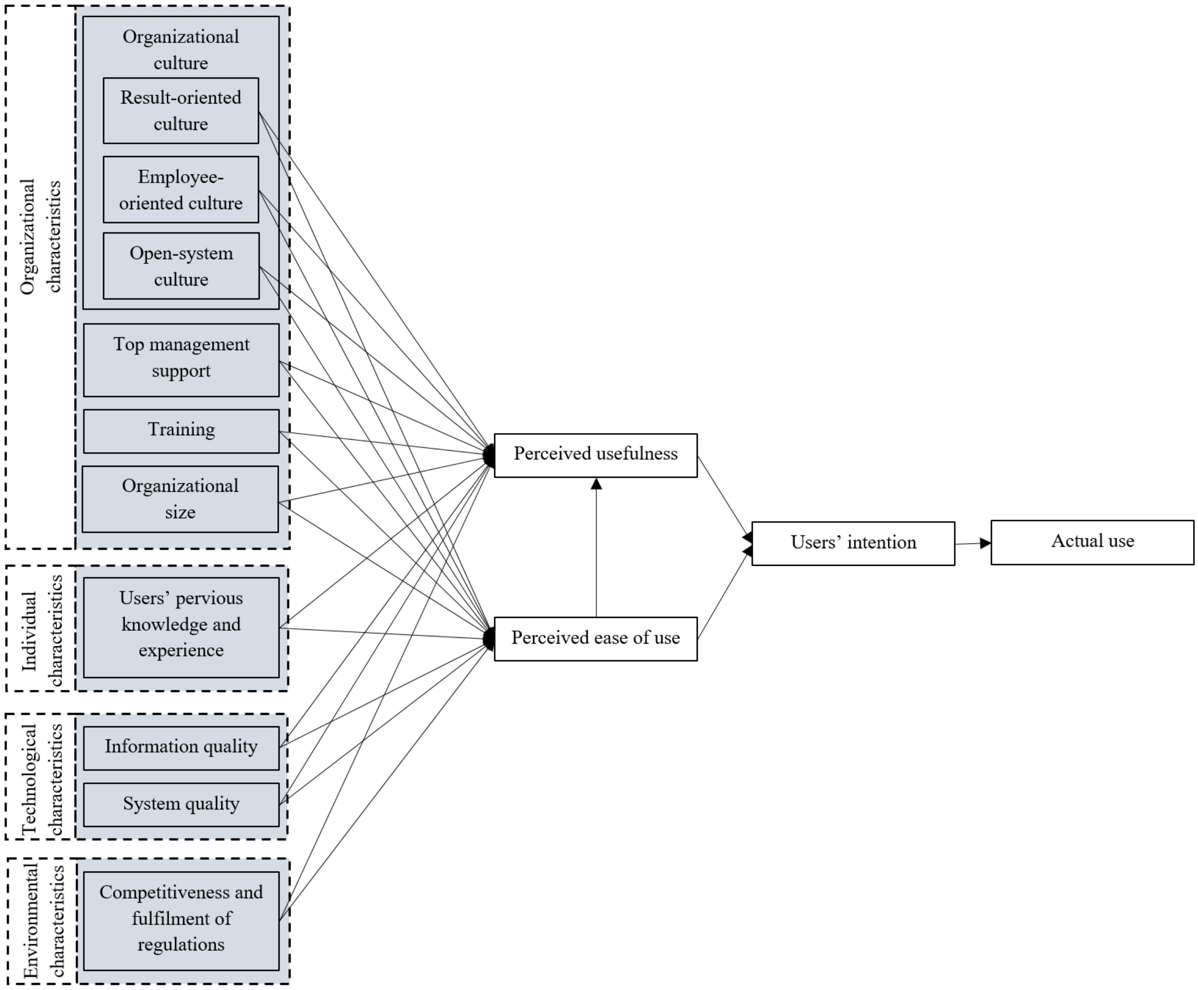


Figure 2: The extended version of TAM

5. Conclusion

Ambitious targets were set in Sweden, which binds the country to achieve 50% more efficient energy use by 2030. Although several attempts were made to achieve the abovementioned target, the energy consumption within the building and service sector in Sweden remained unchanged. At this point, selecting a suitable window design can reduce the energy performance of buildings, in addition, it contributes to improved indoor environmental quality and reduced cost. For this purpose, a computer-based system was previously developed, which allows selecting a suitable window design. The computer-based system was intended to be used in a large-size window and door manufacturing company in Sweden. Although, the strength of the computer-based system in selecting a suitable window design was tested and found appreciated, benefits expected from its implementation cannot be realized unless users accept using it in design practices. Former literature has mainly employed the technology acceptance model (TAM) to investigate the determinants of users' acceptance of a computer-based model. The TAM allows analyzing the effect of external variables on users' intention and actual system use. Successful application of TAM is highly dependent on the specification of external variables. Accordingly, this study conducted a literature review to determine external variables, influencing users' acceptance of a computer-based system, thereby it extended TAM. Former literature considered multiple external variables and analyzed their effect on users' acceptance. However, the most influential variables can be categorized into organizational, individual, technological and environmental characteristics. Organizational characteristics comprised mainly top management support, training, organizational culture, and organizational size, while individual characteristics included users' previous knowledge and experience. Technological characteristics contained information quality and system quality, meanwhile environmental characteristics included fulfillment of regulations and competitiveness.

The extended TAM differs from other available theories and models, used when investigating users' acceptance: "media richness", "social presence", "unified theory of acceptance and use of technology (UTAUT)", and "technology, organization, environment framework" (TOE). The media richness theory concentrates on abilities of communication mediums as computer-based systems in delivering rich information (Oliver, 2019; Watjatrakul & Barikdar, 2007), while social presence theory addresses the degree of salience (i.e., state of being connected) between users of the communication medium (Oliver, 2019; Watjatrakul & Barikdar, 2007). The abovementioned theories have mainly analyzed how communication mediums as computer-based systems facilitates sending rich information and how they improve the quality of human-to-human communications and interactions (Sallnäs, 2004). But TAM concentrates mainly on human-to-computer interactions and provides insight about external variables, which determine users' acceptance. The UTAUT and TOE were commonly used when investigating users' acceptance, but they were criticized due to some limitations. The UTAUT considers only the indirect effect of users' intention on actual system use (Moghavvemi, Salleh, & Abessi, 2013). Furthermore, UTAUT is limited due to its inflexibility to be adapted to different contexts (Al-Gahtani, Hubona, & Wang, 2007). The TOE is only a taxonomy of drivers with no clear constructs, hence it should be further developed to represent an integrated conceptual framework (Dedrick & West, 2003). But the extended TAM considers intention as direct determinants of actual system use (Dedrick & West, 2003), furthermore it functions fully across cross-cultural boundaries (McCoy, Everard, & Jones, 2005), thereby the extended TAM overcomes limitations with the application of UTAUT. In addition, the extended TAM has explicit constructs, which allows one to trace the influence of external variables on cognitive beliefs, and thereby their effects on users' intention and actual system use.

The extended TAM was developed by reviewing literature from manufacturing, architecture, and construction disciplines; accordingly, it can be employed to investigate users' acceptance of a computer-based system within these disciplines. However, the extended TAM can be criticized due to its inherent limitations (Salovaara & Tamminen, 2009). When using the extended TAM, one should conduct questionnaire research method to gather and analyze users' acceptance toward a computer-based system. However, users may have different understandings about the questions (Salovaara & Tamminen, 2009). For instance, a user may concentrate on utility of a computer-based system, while another user may focus on enjoyment, when answering questions. To overcome the abovementioned limitation, one should design the questionnaire in a way to include users' possible understandings. Furthermore, users may have different perceptions in different situations and timeframes (Liu, Lu, & Niu, 2018). Conducting longitudinal studies can help to include variations in users' perception and thereby overcome the latest limitation in using extended TAM. The future work of this literature review includes the application of the extended TAM when investigating determinants of users' acceptance of the computer-based system in the manufacturing company in Sweden.

Acknowledgments

This literature review is part of ProWOOD Ph.D. project, financed by Knowledge Foundation. Authors appreciate their contributions.

References

Acquah, R., & Oteng, D. J. J. o. I. T. i. C. (2018). Acceptance of Building Information Modelling: a survey of professionals in the construction industry in Ghana. *23*(4), 75-91.

Akça, Y., & Özer, G. (2016). Determination the Factors that Affect the Use of Enterprise Resource Planning Information System through Technology Acceptance Model *International Journal of Business and Management, 11*(10).

Al-Fahim, N. H., Jusoh, W. J. W., & Abideen, A. (2014). Factors Affecting the Intention to adopt Internet Banking Services among Small and Medium Sized-Enterprises in Yemen. *Journal of Management and Business Studies, 3*(9), 432-440.

Al-Gahtani, S. S., Hubona, G. S., & Wang, J. (2007). Information technology (IT) in Saudi Arabia: Culture and the acceptance and use of IT. *Information & management, 44*(8), 681-691.

Al Haderi, S., Fareen Abdul Rahim, N., & Mohammed Bamahros, H. (2018). Top Management Support Accelerates the Acceptance of Information Technology. *Social sciences, 13*(1), 175-189

Arnold, H. M. (2012). *Technology shocks: Origins, managerial responses, and firm performance*: Springer Science & Business Media.

Chismar, W. G., & Wiley-Patton, S. (2003). *Does the extended technology acceptance model apply to physicians.* Paper presented at the 36th Annual Hawaii International Conference on System Sciences, 2003. Proceedings of the.

Cho, V. (2007). A study of the impact of organizational learning on information system effectiveness. *International Journal of Business Information*

2(1).

Ciganke, A. P., Mao, E., & Srite, M. J. I. J. o. K. M. (2008). Organizational culture for knowledge management systems: a study of corporate users. *4*(1), 1-16.

Dedrick, J., & West, J. (2003). *Why firms adopt open source platforms: a grounded theory of innovation and standards adoption.* Paper presented at the Proceedings of the workshop on standard making: A critical research frontier for information systems.

DeLone, W., McLean, E. J. O., & out of mind, B. (1999). Information System Success: The Quest for the Dependent Variable," Information Systems Research,(3: 1) pp. 60-95 Dillman, DA, 1978Mail and Telephone Surveys: The Total Design Method, New York: Wiley Donahue, S. 1999. *2*, 1996.

Gangwar, H., Date, H., & Raoot, A. (2014). Review on IT adoption: insights from recent technologies. *Journal of Enterprise Information Management, 27*(4), 488-502.

Goverment Officies of Sweden. (2019). Retrieved from https://www.government.se/ Accessed March 2019

Gupta, K. P., Singh, S., & Bhaskar, P. (2016). Citizen adoption of e-government: a literature review and conceptual framework. *Electronic Government, an International Journal, 12*(2), 160-185.

Hameed, M. A., & Arachchilage, N. A. G. (2017). A Conceptual Model for the Organisational Adoption of Information System Security Innovations. *Journal of Computer Engineering & Information Technology, 6*(2), 1-10.

Hee, W. J., Alghoul, M. A., Bakhtyar, B., Elayeb, O., Shameri, M. A., Alrubaih, M. S., & Sopian, K.

(2015). The role of window glazing on daylighting and energy saving in buildings. *Renewable and Sustainable Energy Reviews, 42*, 323-343. doi:https://doi.org/10.1016/j.rser.2014.09.020

Hofstede, G., Neuijen, B., Ohayv, D. D., & Sanders, G. J. A. s. q. (1990). Measuring organizational cultures: A qualitative and quantitative study across twenty cases. 286-316.

Hua, G. B. (2007). Applying the strategic alignment model to business and ICT strategies of Singapore's small and medium-sized architecture, engineering and construction enterprises. *25*(2), 157-169.

Jalilzadehazhari, E., Johansson, J., & Mahapatra, K. (2018). Applying a decision-making framework for resolving conflicts when selecting windows and blinds. *Architectural Engineering and Design Management*.

Jalilzadehazhari, E., Johansson, P., Johansson, J., & Mahapatra, K. (2018). Developing a decision-making framework for resolving conflicts when selecting windows and blinds. *Architectural Engineering and Design Management*.

Jones, R. A., Jimmieson, N. L., & Griffiths, A. J. J. o. M. S. (2005). The impact of organizational culture and reshaping capabilities on change implementation success: The mediating role of readiness for change. *42*(2), 361-386.

Kamel, S. (2010). *E-strategies for technological diffusion and adoption: National ICT approaches for socioeconomic development: national ICT approaches for socioeconomic development*: IGI Global.

Lee, S., Yu, J., & Jeong, D. J. J. o. M. i. E. (2013). BIM acceptance model in construction organizations. *31*(3), 04014048.

Legris, P., Ingham, J., Collerette, P. J. I., & management. (2003). Why do people use information technology? A critical review of the technology acceptance model. *40*(3), 191-204.

Lewis, W., Agarwal, R., & Sambamurthy, V. (2003). Sources of influence on beliefs about information technology use: An empirical study of knowledge workers. *MIS quarterly*, 657-678.

Liao, S., Hong, J.-C., Wen, M.-H., Pan, Y.-C., Wu, Y.-W. J. E. J. o. M., Science, & Education, T. (2018). Applying Technology Acceptance Model (TAM) to explore Users' Behavioral Intention to Adopt a Performance Assessment System for E-book Production. *14*, 10.

Lin, H.-F. J. I. R. (2007). The role of online and offline features in sustaining virtual communities: an empirical study. *17*(2), 119-138.

Liu, D., Lu, W., & Niu, Y. (2018). Extended technology-acceptance model to make smart construction systems successful. *Journal of Construction Engineering and Management, 144*(6), 04018035.

Lu, Y., Li, Y., Skibniewski, M., Wu, Z., Wang, R., & Le, Y. (2014). Information and communication technology applications in architecture, engineering, and construction organizations: A 15-year review. *Journal of Management in Engineering, 31*(1), A4014010.

Lundström, L. (2016). *Heat demand profiles of buildings' energy conservation measures and their impact on renewable and resource efficient district heating systems.* Mälardalen University,

Mahomed, A. S. B., Mcgrath, M. G., Yuh, B. Z., Othman, Z., Manavalan, K., & Raman, K. (2017). The Influences of Organisational Culture on Email Usage in Malaysian Private Universities. *11*.

Mansor, M., Tayib, D. J. I. J. o. B., & Science, S. (2010). An empirical examination of organisational culture, job stress and job satisfaction within the indirect tax administration in Malaysia. *1*(1).

McCoy, S., Everard, A., & Jones, B. M. (2005). An examination of the technology acceptance model in Uruguay and the US: A focus on culture. *Journal of Global Information Technology Management, 8*(2), 27-45.

Moghavvemi, S., Salleh, N. A. M., & Abessi, M. (2013). Determinants of IT-related innovation acceptance and use behavior: Theoretical integration of unified theory of acceptance and use of technology and entrepreneurial potential model. *Social technologies, 3*(2), 243-260.

Mohd, H., Syed-Mohamad, S.-M., & Zaini, B. J. (2005). CORRELATION BETWEEN INFORMATION QUALITY, USER ACCEPTANCE AND DOCTORS'ATTITUDE OF EMR SYSTEM. *ICOQSIA 2005, 6-8 December, Penang, Malaysia*, 1-6.

Nikas, A., Poulymenakou, A., & Kriaris, P. J. A. i. c. (2007). Investigating antecedents and drivers affecting the adoption of collaboration technologies in the construction industry. *16*(5), 632-641.

Oliver, S. (2019). Communication and trust: rethinking the way construction industry professionals and software vendors utilise computer communication mediums. *Visualization in Engineering, 7*(1), 1.

Park, Y., Son, H., & Kim, C. (2012). Investigating the determinants of construction professionals' acceptance of web-based training: An extension of the technology acceptance model. *Automation in Construction, 22*, 377-386.

Peansupap, V., & Walker, D. H. (2004). *Strategic adoption of information and communication technology (ICT): case studies of construction contractors.* Paper presented at the 20th Annual ARCOM Conference.

Peansupap, V., & Walker, D. H. (2006). Innovation diffusion at the implementation stage of a construction project: a case study of information communication technology. *Construction management and economics, 24*(3), 321-332.

Peansupap, V., & Walker, D. H. J. E. J. o. I. T. i. C. (2005). Factors enabling information and communication technology diffusion and actual implementation in construction organisations. *10*(14), 193-218.

Ruppel, C. P., & Harrington, S. J. J. I. t. o. p. c. (2001). Sharing knowledge through intranets: A study of organizational culture and intranet implementation. *44*(1), 37-52.

Saadé, R. G., & Kira, D. (2007). Mediating the impact of technology usage on perceived ease of use by anxiety. *Computers & education, 49*(4), 1189-1204.

Sallnäs, E.-L. (2004). *The effect of modality on social presence, presence and performance in collaborative virtual environments.* KTH,

Salovaara, A., & Tamminen, S. (2009). Acceptance or appropriation? A design-oriented critique of technology acceptance models. In *Future interaction design II* (pp. 157-173): Springer.

Shih, C.-F., & Venkatesh, A. (2004). Beyond adoption: Development and application of a use-diffusion model. *Journal of marketing, 68*(1), 59-72.

Son, H., Lee, S., Hwang, N., & Kim, C. (2014). *The adoption of building information modeling in the design organization: An empirical study of architects in Korean design firms.* Paper presented at the ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction.

Swedish Energy Agency. (2019). Energy in Sweden - 2018 Retrieved from http://www.energimyndigheten.se/en/news/2018/energy-in-sweden---facts-and-figures-2018-available-now/ Accessed March 2019

Tahilramani, R. J. A. s. i. E.-J. o. o. R. i. m. a. (2013). The Influence of Organizational Culture on Training Effectiveness.

Tatari, O., Castro-Lacouture, D., & Skibniewski, M. J. J. C. I. (2007). Current state of construction enterprise information systems: survey research. *7*(4), 310-319.

To, W.-M., Lee, P. K., & Lam, K.-H. (2018). Building professionals' intention to use smart and sustainable building technologies–An empirical study. *PloS one*, *13*(8), e0201625.

United Nations. (2019). Retrieved from https://unfccc.int/ Accessed March 2019

Usman, N., & Said, I. J. E. J. o. S. R. (2012). Technology acceptance model (TAM) in a multicultural developing nation's construction industry's ICT. *81*(4), 582-588.

Wang, W.-T., Wang, C.-C. J. C., & Education. (2009). An empirical study of instructor adoption of web-based learning systems. *53*(3), 761-774.

Watjatrakul, B., & Barikdar, L. A. (2007). *E-service in Education: The Influences of Media Richness, Social Presence, Privacy and Technology Acceptance Model on Email Adoption.* Paper presented at the the 6th International Conference on e-Business, Bangkok.

Venkatesh, V., & Davis, F. D. J. D. s. (1996). A model of the antecedents of perceived ease of use: Development and test. *27*(3), 451-481.

Venkatesh, V., & Davis, F. D. J. M. s. (2000). A theoretical extension of the technology acceptance model: Four longitudinal field studies. *46*(2), 186-204.

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. *MIS quarterly*, 425-478.

Xu, J., & Quaddus, M. J. J. o. M. D. (2005). Exploring the perceptions of knowledge management systems. *24*(4), 320-334.

Integrated Process & Automated Approaches

Automatic MEP Knowledge Acquisition Based on Documents and Natural Language Processing

Shuo Leng[1], Zhen-Zhong Hu[1,2*], Zheng Luo[3], Jian-Ping Zhang[1] and Jia-Rui Lin[1]
[1] Department of civil engineering, Tsinghua University, Beijing, China
[2] Graduate school at Shenzhen, Tsinghua University, Shenzhen, China
[3] Glodon Technology Inc., Beijing, China
* email: huzhenzhong@tsinghua.edu.cn

Abstract

Mechanical, Electrical and Plumbing (MEP) systems are critical assets in buildings. A series of systematic specifications have been developed and extensive experiences have been accumulated as human knowledge to guide the design and maintenance of MEP systems. However, most of the MEP-related knowledge is represented in the form of unstructured texts and heterogeneously dispersed in the design documents and Internet. It is therefore difficult for managing, querying and utilizing them. To address this challenge, the research study described in this paper constructed a knowledge graph by automatic collecting and storing of MEP knowledge from unstructured data. Specifically, the MEP documents were first acquired from the Internet, and multiple Natural Language Processing (NLP) techniques were then adopted to extract entity and discover relationship from the information documented in these documents. Finally, the knowledge graph was established and presented in a vivid form. The constructed knowledge graph is expected to contribute to the promotion of AI technology in the Architecture, Engineering and Construction (AEC) industry.

Keywords: MEP, Knowledge graph, NLP

1. Introduction

Modern Mechanical, Electrical and Plumbing (MEP) systems consist of multiple subsystems such as energy management, Heating, Ventilation and Air Conditioning (HVAC), water supply, lighting and emergency alarms, etc. (Hu, Tian, Li, & Zhang, 2018). With the development of the MEP engineering, knowledge has been accumulated in the community to improve system efficiency and reduce failures. Generally, knowledge is defined as a collection of descriptions, relationships, and processes in specific domains (Zhou, 2010). In the MEP domain, knowledge is described in industry specifications, technical manuals, research literature and encyclopedias. These documents specify the characteristics, attributes, and operation and inspection methods of MEP facilities, and describe how these facilities work together in a system. The knowledge guides building engineers to design and operate MEP systems in an efficient and reliable way.

The MEP-related knowledge is primarily written by design and operation professionals using human language and presented in the form of text documents. Although these unstructured texts can be easily understood by humans, computers cannot acknowledge their meanings other than character codes. As a result, this data is only stored in computer systems for people to manually access. Meanwhile, as the knowledge is massively and heterogeneously dispersed on the Internet, information from different sources may be duplicated or conflicted, and errors may exist, which makes it difficult to manually collect and organize this knowledge in a systematic way. Junior MEP engineers would have difficulties in learning the knowledge. Moreover, the lack of high-quality, structured data has limited the Artificial Intelligence (AI) applications such as intelligent question-answering, and knowledge search and inference in the MEP field.

To address this challenge, the research study discussed in this paper constructed a knowledge graph by automatic collect and store MEP knowledge from the Internet. The knowledge graph is designed to organize entities and their relationships in the form of a semantic network, in which entities refer to concepts, terms, or anything else that can be called knowledge (Paulheim, 2017). With this structure, the entity can be accurately positioned, and things related to it can be quickly detected. The knowledge graph can be further used as databases for knowledge representation, search, inference and data mining, and has achieved successful applications in some industries (H. Wang, Miao, & Yang, 2018).

In order to construct the knowledge graph, text documents were first obtained from the internet, and multiple Natural Language Processing (NLP) techniques were applied. The structure of the paper is organized as follows: Section 2 investigates relevant literature on intelligent MEP and knowledge engineering. Section 3 introduces some necessary techniques in achieving automatic MEP knowledge acquisition. The next section gives a case study to present the constructed knowledge graph and evaluates its performance. Finally, the discussion and conclusion are given.

2. Related Research Studies

The application of computers and automated methods to improve the traditional construction and management process has been one of the researches focuses in the MEP field. Through a specially designed algorithm, the computer can detect the potential spatial conflicts of MEP components (L. Wang & Leite, 2016), or help designers detect drawing errors according to the design rules (Korman, Fischer, & Tatum, 2003). Building Information Modeling (BIM) technology can also be applied to the MEP field to improve the efficiency of facility management (Hu, et al., 2016). Though these studies provided automated solutions for those heavy repetitive tasks, the MEP knowledge they need, such as the rules of collision detection or the initial database for reasoning, still had to be manually collected and imported, which was time-consuming and limited further development of automation technology.

Establishing a unified and integrated knowledge base is a feasible way to solve knowledge problems. In the Architecture, Engineering and Construction (AEC) industry, the BIM-based semantic web is an effective method for knowledge management and representation (Pauwels, et al., 2017). The semantic web, which is a concept extended by the World Wide Web (WWW), is used to fuse and store information from different data sources by defining ontologies and their relationships (Berners-Lee, et al., 2001). Through the semantic web, BIM can integrate different aspects of information such as energy consumption (Jiang, et al., 2018) and be further applied to knowledge reasoning (Bouzidi, et al., 2012). However, in the MEP field, works related to semantic web have not been seen in the literature. Even in the AEC field, the construction of the semantic web mainly follows a top-down process, which means that the semantic web needs to first determine the top-level concepts by domain experts, and then divide the instances into the corresponding concepts (Turk, 2006). A large amount of manual participation lead the semantic web limit in size, and the fixed top-level concepts also make it difficult for the database to be modified with the rapid update of knowledge in the network.

The term knowledge graph was originally proposed by Google in 2012 to name their semantic web products for search engines, and then extended to a concept referring to the web-based semantic web databases (Paulheim, 2017). In addition to the Google Knowledge Graph, some instances of general knowledge graph include DBpedia (Lehmann et al., 2015) and YAGO (Fabian, Gjergji, & Gerhard, 2007) were also presented in the common field. In the AEC industry, a geotechnical knowledge graph has been proposed and established (C. Wang, et al., 2018). Compared with the traditional semantic web, these knowledge graphs are equipped with information acquisition and processing algorithms and can be expanded automatically by extracting knowledge from the network. As a result, the knowledge graph is generally larger in scale and requires less human involvement.

Based on the knowledge graph, many successful applications of AI techniques have been achieved. For example, knowledge graphs can be used as databases for Q&A systems(Sawant, et al., 2019). Entities in the question statement can be extracted by decoding techniques, and the information of the entity in the graph can be provided to the user as answers. Knowledge graphs can also be used to support recommender systems (Wang, et al., 2018). The potential interests of the user can be extended as relationships among entities. When an entity is selected, other entities associated with it will be recommended to the user. A knowledge graph in the MEP field can promote such AI applications in the industry, providing convenience for MEP industry practitioners.

3. Primary Approaches

3.1 Data acquisition and preprocessing

The data used in the paper were derived from text documents (in the form of PDF, Word, and HTML) related to the MEP domain from the Internet. A crawler program was developed in this research to obtain documents from some typical MEP websites. Then these data were merged together to form the raw dataset for the study.

During the preprocessing process, data cleaning and format conversion were first performed. Then the text segmentation process, which divided a sequence of words into separate words, was executed. For English texts, words are always separated by spaces, and the segmentation is naturally completed. However, in Chinese, there is no obvious separation between words, and the process of text segmentation is thus indispensable (Wu & Tseng, 1993).

3.2 MEP Entity Extraction

The target of entity extraction is to automatically discover the MEP related entities in the text. This process utilizes the Named Entity Recognition (NER) technology. The entities here refer to MEP terms include facilities, operations and attributes, and they will participate in the construction of knowledge graph as network nodes. Several types of practical NER techniques have been proposed, and the model Bidirectional Long Short Term Memory (Bi-LSTM) network with a Conditional Random Field layer (Bi-LSTM-CRF) which has been proved to have a considerably good performance (Z. Huang, et al.,

2015) was applied to implement this process. The Bi-LSTM-CRF method converts the entity recognition process into a sequence labeling task and outputs the labeling results with the highest occurrence probability. The model structure of the Bi-LSTM-CRF is shown in Figure 1.

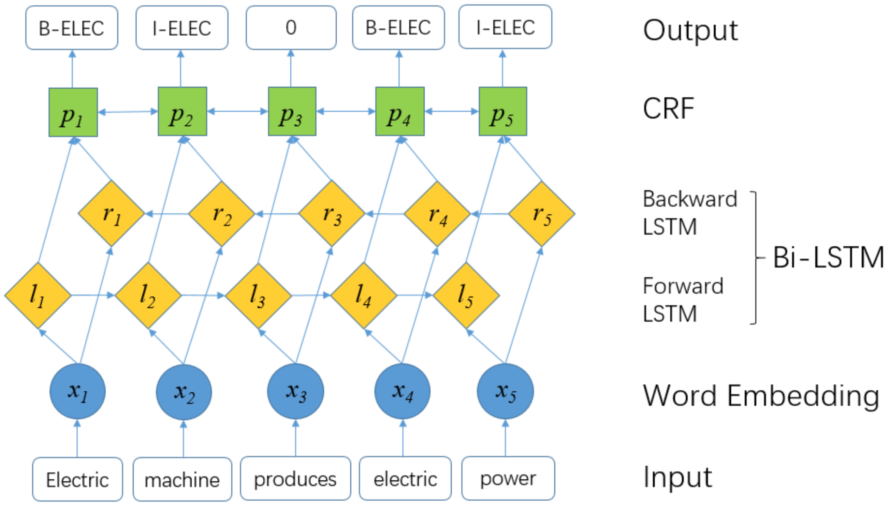


Figure 1: Structure of the Bi-LSTM-CRF model

The Bi-LSTM-CRF model consists of three parts: the word embedding layer, the Bi-LSTM layer, and the CRF layer. The model receives the word sequence in natural language as input variables and outputs a predictive label for each word after a series of calculations. Specifically, the word embedding layer converts each word into a vector, and the Bi-LSTM layer maps the vector to the probability of each label. Subsequently, the CRF layer adjusts the likelihood of the label based on probability theory, and the category with the highest probability is selected as the output label. Words with some specific labels are eventually determined to be named entities.

3.3 Entity Relationship Discovery

The entity relation discovery process is used to obtain the relationships between entities that act as direct edges in the knowledge graph, connecting entity nodes to form a network structure. These relationships show how the MEP entities connected to each other logically and work together. Multiple algorithms from rule-based methods to deep learning have been proposed for relationship discovery in this research. A Residual Convolutional Neural Network (ResCNN) model was adopted for its high accuracy and fast training speed (Y. Huang & Wang, 2017). The structure of ResCNN is illustrated in Figure 2.

Similar to the entity discovery process, each word needs to be converted to a vector at the beginning of the ResCNN model. Vectors of the entire sentence are then concatenated to a matrix and imported to the core model. The structure of the core ResCNN is basically the same as that of general CNN, including the convolution layer, pooling layer, full connection layer, and Softmax process. However, ResCNN adds a shortcut between every two or three convolutional layers so that the input value can directly participate in the calculation of the predicted result. Such a structure is called a residual block. In this way, instead of the predicted value, the learning target of the network focuses on the residual that is obtained by subtracting the input value from the predicted value. The final output of the model is the probability of each relationship, and the category with the highest probability is selected as the relationship between the two entities.

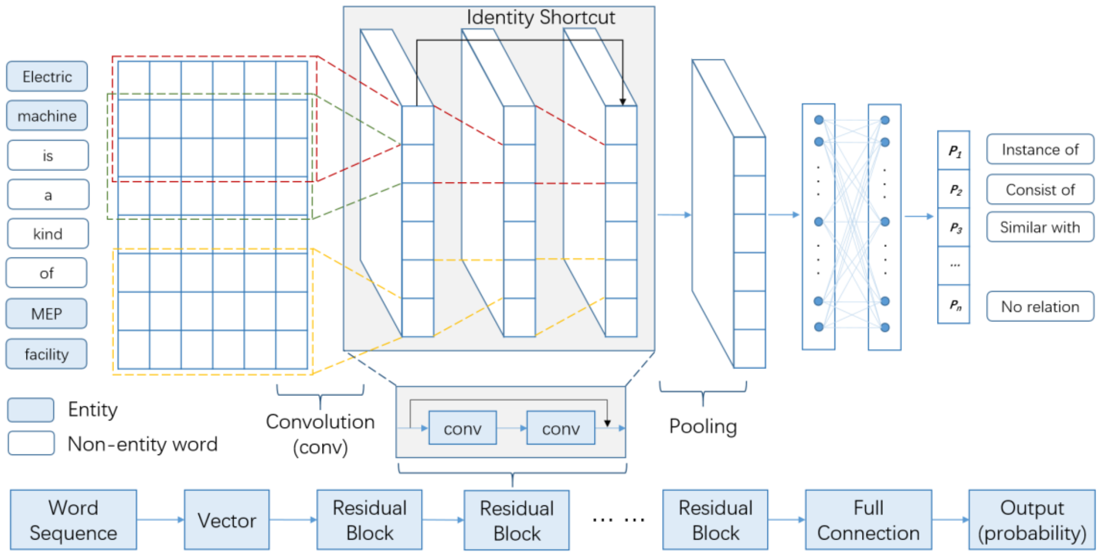


Figure 2: Structure of the ResCNN model

4. Case Study

In this paper, MEP text documents were collected from multiple websites on the Internet. The data consists of sub-datasets including industry specifications, research literature, encyclopedia, Q&A corpus and MEP component library. The raw text is 70M in size and contains more than 14 million words.

As a data preprocessing step, the word segmentation was performed to split the words from sentences. In the proposed approach, the text segmentation tool Jieba (Fxsjy, 2019) was applied to complete this process. The split words were then used as input variables for subsequent NLP models. Among them, 40% of the corpus was randomly selected for model training, and the rest was used for entity extraction after the model was fully trained.

Since machine learning methods convert entity recognition into tasks of sequence labeling, characters in the text need to be labeled before the algorithm is executed. In this research, the labeling method marked with BIO was adopted. The notation B represents the starting character of an entity, I represent the subsequent character of an entity, and O indicates a non-entity character. Three categories of entities were identified in the proposed approach including electric, HVAC, and water supply and drainage. The introduction and examples of the labeling method are shown in Table 1 and Figure 3 respectively. A dictionary mapping method which automatically labels texts by judging whether the word is in a pre-prepared MEP dictionary was adopted in this paper.

The marked text sequences were input to the Bi-LSTM-CRF model for training, and the fully trained model could then be used to predict the label for new texts as the NER process. 15 epochs were performed before the final prediction model was obtained. The predicted results of the model on the test dataset are illustrated in Table 2.

Table 1: Introduction to the sequence labeling method

Label	Explanation
B-E	Beginning character of an electric entity
B-H	Beginning character of an HVAC entity
B-W	Beginning character of a water supply and drainage entity
I-E	Subsequent character of an electric entity
I-H	Subsequent character of an HVAC entity
I-W	Subsequent character of a water supply and drainage entity
O	Characters that do not belong to entities

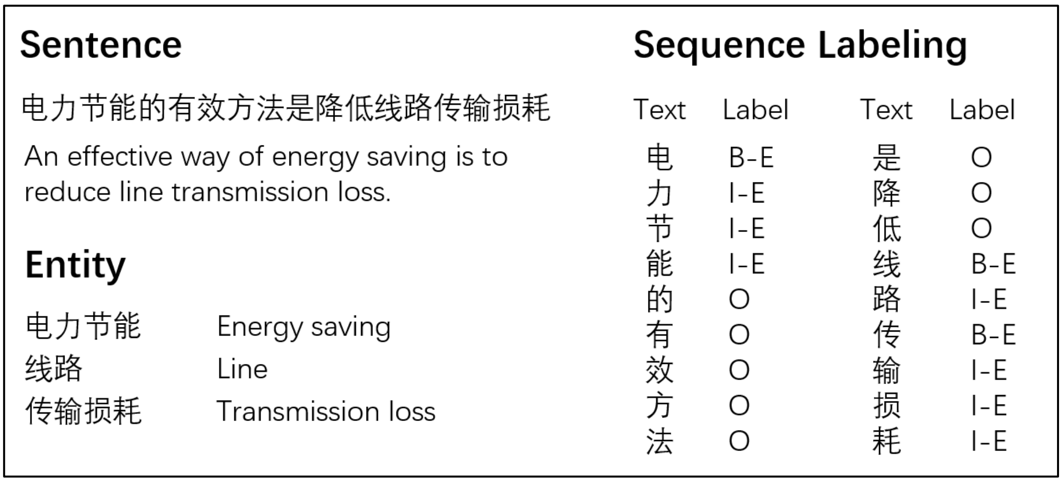


Figure 3: Instance of sequence labeling

Table 2: Training results of the Bi-LSTM-CRF model

Entity categories	Precision	Recall	F1 Score
Electric	97.01	97.97	97.49
HVAC	96.48	97.91	97.19
Water supply and drainage	96.15	97.53	96.84
Total	96.78	97.90	97.34

As can be concluded, the overall accuracy of the model is over 97%, which is a relatively high value compared with other state-of-the-art NER models. After the end of the NER program, a manual screening process was further executed to delete the entities found by mistake and improve the quality of the entity dataset. A total of 11332 MEP entities were eventually extracted.

After the NER process, the discovered entities were marked in the corpus and the relationship discovery was subsequently performed. As illustrated in Table 3, 4 types of relationships, including “have attribute”, “instance of”, “similar to” and “contain”, were defined to represent interactions between MEP entities. The relationship “instance of” could be judged by syntactic analysis, and the other categories were evaluated by the ResCNN model. Sentences in the corpus that contain two or more entities were selected as datasets for relationship discovery. Among them, relationships of entity pairs in 900 sentences were manually labeled to train the model, and the remaining sentences were used for relationship discovery.

Table 3: Introduction to the relation category

Relationship categories	Explanation	Example
Have attribute	"Entity A has attribute Entity B" means that B is an attribute of A	A: air conditioning B: power
Instance of	"Entity A is an instance of Entity B" means that B is a general concept and A is a special case of B	A: valve B: fire control valve
Similar to	"Entity A is similar to Entity B" means that A and B is similar in function or concept	A: plug B: socket
Contain	"Entity A contains Entity B" means that B is a physical component of A	A: air conditioning B: air compressor

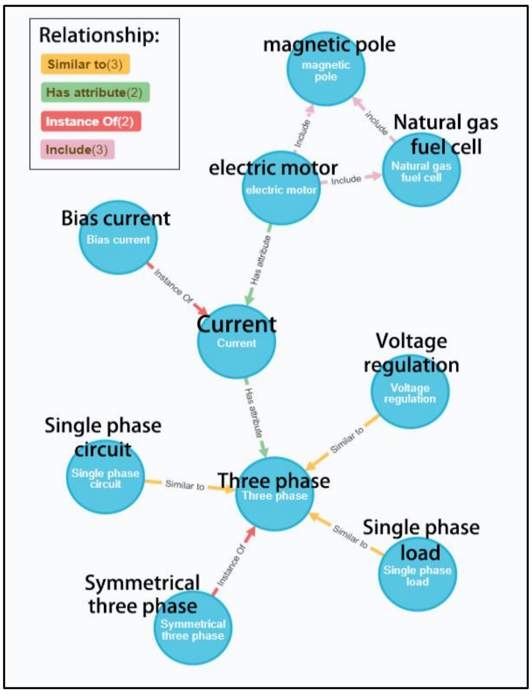
The ResCNN model took 200 epochs of training to achieve stable performance. Subsequently, a test process was performed to evaluate the prediction accuracy of the model, and the results are shown in Table 4. The general accuracy of the model is around 70%, which is relatively acceptable. However, the performance of the model is much poorer than that of the NER model, probably because here the training data set needs to be manually labeled and is thus much smaller. After the program finished, a manual inspection process was also carried out to improve the quality of the relationships. As a result, a total of 9439 relations were discovered.

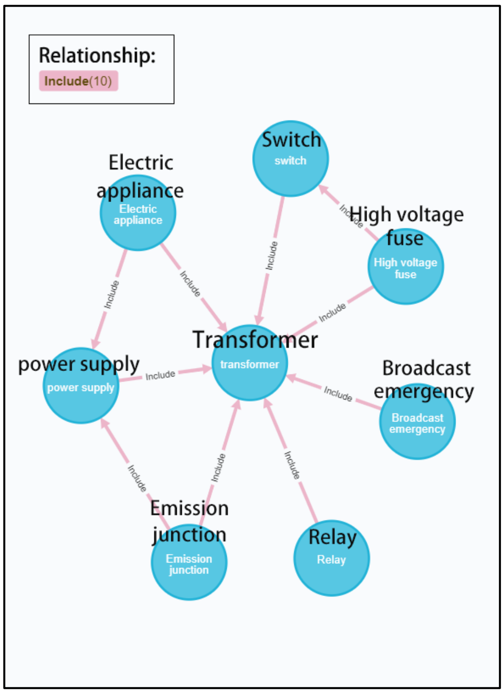
Table 4: Training results of the ResCNN model

Relationship categories	Precision	Recall	F1 Score
No relationship	57.43	75.35	64.67
Instance of	58.90	89.87	70.69
Similar to	87.00	84.37	85.17
Contain	79.07	51.37	61.80
Total	70.60	75.24	70.58

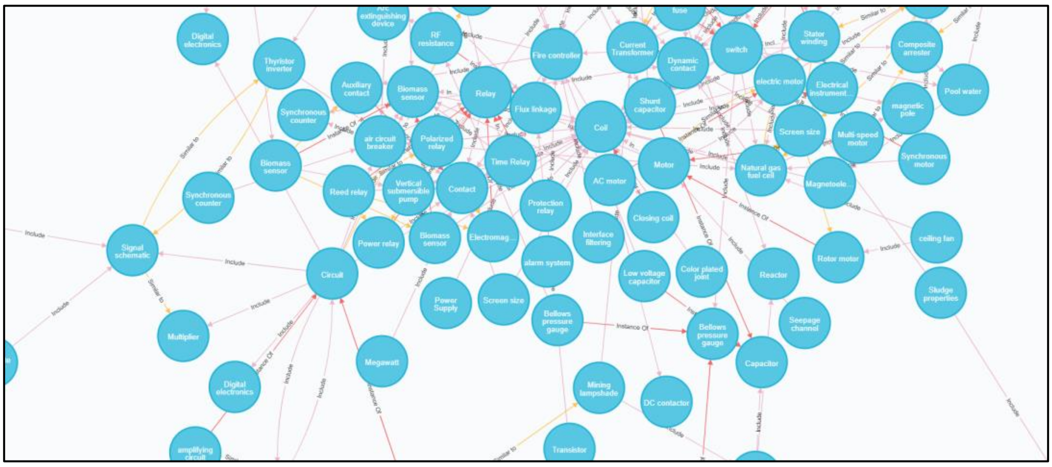
After the knowledge acquisition process, the entities and relationships were merged together to construct a knowledge graph. In the proposed approach, a graph database Neo4j (Neo4j, 2019) was applied to store and visualize this knowledge. The graph database records data in the form of nodes and edges, which enables faster modification and query speed for graph-based data than traditional relational databases. In this graph database, the MEP entities were applied as nodes in the graph, and their relationships were taken as edges. A part of the constructed knowledge graph is shown in Fig. 4a. Compared with plain texts or tables, the knowledge graph can present MEP knowledge more systematically, concisely and intuitively. A more complex part of the graph is shown in Fig. 4c, illustrating the knowledge is connected together to form a network structure.

Based on the graph database, the knowledge query function can be further implemented. For example, one might be interested in what MEP facilities contain a transformer as a component. The graph database can quickly return results to him from tens of thousands of knowledge with just one command, as shown in Fig. 4b. This query is hard to accomplish for text-based data even with the help of the Internet.





(a). part of the Knowledge graph *(b). Search result of "Transformer"*



(c). a more complex part of the Knowledge Graph

Figure 4: Visualization of the MEP Knowledge graph (Translated into English)

5. Discussion and Conclusion

Although only simple knowledge-graph-based functions such as visualization and node search were achieved in this paper, the role of knowledge graph goes far beyond this. Proved by the famous search engine Google, knowledge graph can sort out the domain knowledge without the help of experts and become the basis of ontology construction. Moreover, the knowledge graph can be used as databases of various AI applications such as reasoning and dialog system.

Though the method to establish the MEP knowledge graph is tested to be feasible in this research, it should be pointed out that the proposed knowledge graph is far from perfect and requires further researches and works. The scale of the graph needs to be expanded as the data source is not comprehensive and the amount of data is insufficient. At the same time, the knowledge extraction algorithm needs to be modified to improve its performance. Knowledge fusion and disambiguation also need to be processed to improve the quality of the graph.

As a conclusion, a MEP knowledge graph which is a systematic summary of the fragmented texts in the network was constructed in this research. To achieve the automatic MEP knowledge acquisition, a diverse range of MEP text documents were obtained from the network, and multiple NLP techniques, including word segmentation, entity extraction and relationship discovery, were applied to discover entities and relationships from the text. This knowledge was then organized in the form of a network to represent a knowledge graph. A simple application of the knowledge graph was presented, and possible applications were further discussed. The knowledge graph constructed in this paper is expected to contribute to the promotion of AI technology in the MEP industry.

Acknowledgements

This research was supported by the National Key R&D Program of China (Grant No. 2017YFC0704200), the National Natural Science Foundation (No. 51778336), and the Tsinghua University – Glodon Joint Research Center for Building Information Modelling.

References

Berners-Lee, T., Hendler, J., & Lassila, O. (2001). The semantic web. *Scientific american, 284*(5), 28-37.

Bouzidi, K. R., Fies, B., Faron-Zucker, C., Zarli, A., & Thanh, N. L. (2012). Semantic web approach to ease regulation compliance checking in construction industry. *Future Internet, 4*(3), 830-851.

Fabian, M., Gjergji, K., & Gerhard, W. (2007). *Yago: A core of semantic knowledge unifying wordnet and wikipedia*. Paper presented at the 16th International World Wide Web Conference, WWW.

Fxsjy. (2019). Jieba Chinese text segmentation. Retrieved from https://github.com/fxsjy/jieba

Hu, Z.-Z., Tian, P.-L., Li, S.-W., & Zhang, J.-P. (2018). BIM-based integrated delivery technologies for intelligent MEP management in the operation and maintenance phase. *Advances in Engineering Software, 115*, 1-16.

Hu, Z.-Z., Zhang, J.-P., Yu, F.-Q., Tian, P.-L., & Xiang, X.-S. (2016). Construction and facility management of large MEP projects using a multi-Scale building information model. *Advances in Engineering Software, 100*, 215-230.

Huang, Y., & Wang, W. Y. (2017). *Deep Residual Learning for Weakly-Supervised Relation Extraction*. Paper presented at the Proceedings of the 2017 Conference on Empirical Methods in Natural Language Processing.

Huang, Z., Xu, W., & Yu, K. (2015). Bidirectional LSTM-CRF models for sequence tagging. *arXiv preprint arXiv:1508.01991*.

Jiang, S., Wang, N., & Wu, J. (2018). Combining BIM and Ontology to Facilitate Intelligent Green Building Evaluation. *Journal of Computing in Civil Engineering, 32*(5), 04018039.

Korman, T. M., Fischer, M. A., & Tatum, C. B. (2003). Knowledge and reasoning for MEP coordination. *Journal of Construction Engineering and Management, 129*(6), 627-634.

Lehmann, J., Isele, R., Jakob, M., Jentzsch, A., Kontokostas, D., Mendes, P. N., . . . Auer, S. (2015). DBpedia–a large-scale, multilingual knowledge base extracted from Wikipedia. *Semantic web, 6*(2), 167-195.

Neo4j. (2019). Neo4j Graph Platform – The Leader in Graph Databases. Retrieved from https://neo4j.com/

Paulheim, H. (2017). Knowledge graph refinement: A survey of approaches and evaluation methods. *Semantic web, 8*(3), 489-508.

Pauwels, P., Zhang, S., & Lee, Y.-C. (2017). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction, 73*, 145-165.

Sawant, U., Garg, S., Chakrabarti, S., & Ramakrishnan, G. (2019). Neural architecture for question answering using a knowledge graph and web corpus. *Information Retrieval Journal*, 1-26.

Turk, Ž. (2006). Construction informatics: Definition and ontology. *Advanced engineering informatics, 20*(2), 187-199.

Wang, C., Ma, X., Chen, J., & Chen, J. (2018). Information extraction and knowledge graph construction from geoscience literature. *Computers & Geosciences, 112*, 112-120.

Wang, H., Miao, X., & Yang, P. (2018). *Design and Implementation of Personal Health Record Systems Based on Knowledge Graph*. Paper presented at the 2018 9th International Conference on Information Technology in Medicine and Education (ITME).

Wang, H., Zhang, F., Wang, J., Zhao, M., Li, W., Xie, X., & Guo, M. (2018). *RippleNet: Propagating user preferences on the knowledge graph for recommender systems*. Paper presented at the Proceedings of the 27th ACM International Conference on Information and Knowledge Management.

Wang, L., & Leite, F. (2016). Formalized knowledge representation for spatial conflict coordination of mechanical, electrical and plumbing (MEP) systems in new building projects. *Automation in Construction, 64*, 20-26.

Wu, Z., & Tseng, G. (1993). Chinese text segmentation for text retrieval: Achievements and problems. *Journal of the American Society for Information Science, 44*(9), 532-542.

Zhou, Z. (2010). *Manufacturing Intelligence for Industrial Engineering: Methods for System Self-Organization, Learning, and Adaptation*: IGI Global.

Automation of software independent data interpretation between architectural and structural analysis models

Goran Sibenik[1*] and Iva Kovacic[1],
[1]Institute for Interdisciplinary Building Process Management, TU Wien, Austria
*email: goran.sibenik@tuwien.ac.at

Abstract

In AEC practices multifold digital models exist to support various design and analysis tasks (e.g. architectural or HVAC design, structural or thermal analysis). Information models need to satisfy the particular and varying domain-specific needs. Despite the great efforts to create open standards for data exchange, digital data exchange between domains is still burdened with numerous difficulties, such as loss or wrong interpretation of information. The seamless data exchange between actors in the process would reduce communication-based errors and planning time, and it is a requirement for achieving a full potential of BIM.

This work focuses on the automation of interpretation steps between architectural and structural analysis models with intermediary data available in software independent storage. Previously conducted research identified the need for standardisation of interpretation in order to improve the software-independent data exchange.

Thereby we first review relevant software tools, standards and data exchange processes, where the architectural and structural analysis representations were analysed and the relations between them were identified.

Next, a new framework for data handling in the AEC planning process was created. The data-handling framework is based on domain-specific classification, interpretation and automation procedures that can support interdisciplinary exchange. Classification is needed for systematic arrangement of data in groups or categories according to established criteria, so the data would remain machine readable, and it is based on the IFC taxonomy. Interpretation between architectural and structural analysis models was proposed based on the previously conducted state-of-the-art review. The proposed domain-specific classification and interpretation procedures are developed for the exchange between architecture and structural engineering domains. However, the proposed central data handling framework is generic, so it could be used for other domains in the AEC industry as well. Finally, in the automation procedure, the framework is implemented with the system architecture that can support it. The data is available on a software independent storage, and the domain specific model communicates with the software independent storage. The interpretation is automated with the help of a programming language.

The innovative contribution are primarily the procedural steps defining the interpretation, followed by the proposed framework for the data exchange involving domain-specific classification and interpretation procedures, and finally the automation where a semi-structured database is used for the data storage and interpretations are automated with a programming language. Automating the central storage-based interpretation steps is a crucial feature of a new framework allowing communication between various domain-specific models within software independent storage.

Keywords: data exchange, interpretation steps, automation, structural analysis, open standards

1. Introduction

The architecture, engineering and construction (AEC) industry aims on improving the planning processes with the digitalisation of workflows. One of the key features of a digital workflow is the model-based communication and the seamless data exchange. Structural analysis computes the behaviour of building elements in the most unfavourable situation of load cases. The computations take place with the idealized building elements: punctual, linear and planar elements. Information about building elements originate from the architectural design which is usually a preceding step for structural analysis. The data exchange between architectural and structural analysis models is still done via physical documents (paper), digitised documents (pdf files) or files containing 2D geometry (dwg drawings), while the 3D model-based exchange takes place only in isolated cases and intrafirm workflows. If a 3D building model is created from 2D documents, the geometry needs to be remodelled in a 3D structural analysis tools, which is an expensive, redundant and erroneous work. However, the industry still fails to achieve a model-based exchange which would be trustworthy enough for the end users.

The model-based exchange gains on popularity for its potentials in improving the planning workflows. Depending on the existence of an accessible and modifiable intermediate building data model, two types of data exchange workflows exist: open and closed BIM (Building Information Modelling). Closed BIM is referred to as a workflow where the data exchange takes place with software to software interfaces; Open BIM approach refers to a workflow where an open, non-proprietary format is used for the data exchange purposes. The most widely spread and implemented open standard within the software tools intended for this use is the Industry Foundation Classes (IFC) standard developed by buildingSMART (buildingSMART, 2019). Researchers investigating the data exchange between architecture and structural analysis are focused on the open exchange, especially the IFC standard (e.g. Romberg et al., 2004; Ramaji & Memari, 2018).

In our previous research, the analysis of the open data exchange in practice showed that a crucial requirement for a systematic improvement is interpretation rules between different domains (Sibenik & Kovacic, 2019). These rules are not straightforwardly defined in the standards. The open data exchange framework needs to be improved, so the interpretation rules would become a part it. The analysis showed that a single integrated model supporting various AEC domains does not suffice and the AEC industry is stepping towards multiple domain specific data models and automated or semi-automated interpretation between them. The interpretation steps need to describe the most repetitive tasks in such a way that they could be automated, and at the same time understandable and open to an end user. This paper aims at describing possible interpretation steps between the architectural and structural analysis models.

This work is structured as following: in Section 2 the research background regarding the interpretations between the architectural and structural analysis domains will be explained. In Section 3 we will provide a review of the state of the art of existing software tools, standards and the data exchange workflow. In Section 4 a proposed framework that includes classification, interpretation and automation procedures will be presented. This paper addresses primarily the interpretations, which will be proposed in Section 5. Section 6 will describe a test system architecture, while we conclude with Section 7 with the summary of framework properties and the future outlook.

2. Background

The open model-based exchange between architecture and structural analysis rarely takes place in practice, since it still does not meet the end user requirements. There are several framework proposals using the IFC building data model as a starting point, which is interpreted to a structural analysis model (Deng & Chang, 2006; Hu et al., 2016; Liu et al., 2010; Qin et al., 2011; Ramaji & Memari, 2018; Wang et al., 2013; Zhang et al., 2014). They document significant differences between the architectural and structural analysis models, providing often software tool-related problem-solutions. The problems were addressed on a practical level and while the software-specific solutions give directions for the software-independent framework improvement, they still cannot be generally applied in the AEC industry as such. Various changes in the currently established practices have to be made in order to achieve a working data exchange. Interpretation steps are described based on the input model, focusing mostly on a specific IFC export and creating a new structural analysis model from it. The frameworks using the IFC building data model as a starting point are still software tool-specific because of the IFC schema redundancy. The conceptual differences between the models and the interpretation steps which take place between them are defined for the research purposes and not extensively investigated.

Some researchers question the use of the central integrated model, and pursue the use of multiple models. Rezgui et al. (2011) and Rezgui et al. (2010) propose a process driven framework, which is web-based and supported by ontologies; eventually leading to knowledge value creation from knowledge sharing. Lee et al. (2014) describe a web-based framework involving domain-specific filters as intermediary step between the complex central model and the domain-specific models; stepping away from the concept of integrated model. In our previous research, the necessity to separate multiple domain-specific building data models has been recognized, whereby the relations between multiple models need to be retained and originate from the inter-domain conceptualisation (Sibenik & Kovacic, 2019).

Another problem that we analysed is the data structure in the open central storage: the necessity to separately deal with the geometrical and non-geometrical information was recognised. In most of the proposed frameworks (Deng & Chang, 2006; Lee & Jeong, 2012; Liu et al., 2010; Ramaji & Memari, 2018) both types of information are treated similarly, often focusing on one and applying the same framework to the other, sometimes reflecting the storage structure of structural analysis software tools. Wan et al. (2004) define geometry, loads, materials, member sections and other as separate information gaps, Hu et al. (2016) geometrical, property and control information as parts of the data management layer, and Lee & Jeong (2012) distinct geometric and non-geometric information in the object level of their filter mechanism, but not focusing on geometric interpretations. On the other hand, the ontology, taxonomy and classification related work, is mostly dealing with the non-geometrical information (Pauwels et al., 2017). In order to achieve a seamless communication we propose to use two different approaches for managing geometrical and non-geometrical information. Exchange of geometrical information is dependent on geometrical kernels in the interoperating software tools, interpretations steps and the geometrical definitions supported by the mediatory open standard. The interpretation of the semantic and syntactic description of the building information models does not have much to do with the geometrical data interpretations. Besides that, geometric transformations of building models involve complex geometrical methods, and some researchers already suggested to introduce a geometry kernel in the intermediary translational steps (e.g. Mora et al., 2008; Romberg et al., 2004). However the integral approach which can process both geometrical and non-geometrical information is necessary in the AEC industry.

As already mentioned, the trends in the academic community supports multiple domain-specific models and the interpretation between them, sometimes referred to as filters or pre-processing steps. Although in the analysed papers the interpretations are part of the workflows, the data interpretation steps are simplified and not sufficiently documented; focus either on geometrical or non-geometrical interpretation. The interpretation steps are usually described as the generally accepted truth, although they are based on the intuitive, and commonly software tool or regionally specific workflows. For the automation purposes it is necessary to define the tolerances, borderline cases and all interpretation steps in such a way that the models can be machine processable, and the interpretations understandable by the end users. Because our reasoning brings us to the unavoidable automation of repetitive tasks during the model exchange, with this research we aim to contribute to the body of knowledge that bridges the interdisciplinary differences between architectural and structural analysis models, focusing on the geometric interpretations, but also considering the non-geometric interpretations.

The main research question this paper addresses is: **how to efficiently support the end user needs within the exchange between architectural and structural analysis tools**. We aim to answer this question by providing a data exchange framework which focuses on two procedures: domain-specific classification and interpretation between the domains, implemented using a software independent central storage and processing. In this paper we will focus on the interpretation steps.

3. State of the art

3.1 Software tools

The taxonomy and classes present in software tools are compared in Sibenik & Kovacic (2019). The paper concludes that the objects available in software tools show significant similarities if the tools support a same domain. For example, architectural and structural design software tools (Revit and Allplan) as well as the software for architectural design (Archicad) provide similar classes for the description of column, wall and slab. On the other hand, structural analysis software tools represent these elements as linear (column) or planar (wall and slab). These classes represent same real-world building elements, but they differ between the domains to which they belong. In the planning workflow it is necessary to transfer this information between the domains.

Ramaji & Memari (2018) list three possibilities to create a structural analysis model from a native BIM model: 1. Structural analysis model is created in a native software tool; 2. Structural analysis model is created from a native model in a structural analysis tool; 3. An additional software tool (or a plug-in) is used to generate the structural analysis model. This classification is based on the primary role of the software tool that generates the structural analysis model: architectural tool, structural analysis tool, or a third-party data exchange tool. The interpretations taking place are not open to the end user and generally work as a “black-box” scenario (Holzer et al., 2007). This means that the processes defined within the software tools are not explained to or editable by the end user, and the interventions are limited to the methods defined by the software industry. The lack of interpretation transparency and the lack of support for all necessary user interventions during the exchange process discourages the end users to allow for the automatic exchange.

3.2 Standards

The three building elements (column, wall, slab) are not sufficiently precisely described in the standards so the conversion between their architectural and structural classes could be automated. In fact, the majority of building elements are not sufficiently standardised due to the heterogeneity of the industry and the lack of consideration of automation possibilities. However, there are recommendations for structural engineers (Pech & Kolbitsch, 2005; Schuler, 2016) which suggest how to treat the architectural elements when interpreting them for structural analysis. Standards provide little or no information about the rules of how the elements are interpreted between the domains (e.g. obsolete DIN, 2002).

The most widely implemented standard for the digital exchange between the two domains is the IFC schema. Early works on the schema (Weise et al., 2003) introduced the majority of the structural analysis concepts and their corresponding properties. Current version of IFC schema supports all three analysed elements, both as architectural and structural analysis domain entities. Therefore, a building element instance can occur in a single model multiple times - as structural and architectural element, without any interdependency between the two representations. Relations between the element representations do not exist and they are not included on other levels of the IFC-based data exchange framework like Information Delivery Manuals (IDM) or multiple Model View Definitions (MVD). The main problem of the standard for an interdisciplinary exchange is identified as the missing relations between the elements (Figure 1).

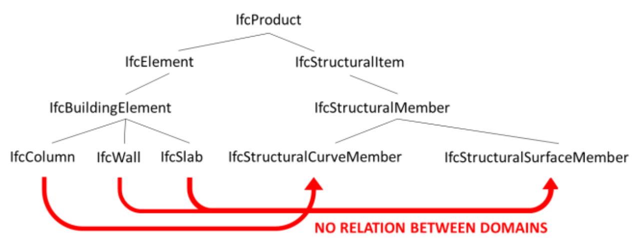


Figure 1 Extract from the IFC 2x3 schema

3.3 Data exchange

In practice, the data exchange process taking place between the architectural and structural analysis models takes place primarily with 2D architectural plans, by remodelling them in the structural analysis software tools. In this work we focus on the 3D model-based open data exchange which still has multiple problems in practice (Sibenik, 2016). We will focus on the end-user need to access and edit not only the building data model, but also the interpretation processes that take place before the import to the structural analysis software.

In practice, the model-based exchange workflows established within the company (intracompany) sometimes have positive outcomes. On the other side, projects based on one-time stakeholder setups rarely achieve a successful model-based exchange. The success is commonly determined by the experience of practitioners with the software tools, and the software tool interoperability. Closed, underlying interpretations within software tools are understood with time, and the successful exchange workflows are developed by adjusting the original workflows to the software performance. However, achieving a successful exchange in this way does not satisfy the majority of end users because it requires adapting to non-intuitional design modelling practices and uncontrolled exchange processes. End users need a fully transparent exchange framework, with transparent model data and interpretation steps to satisfy their design needs.

4. Framework

The proposed framework defines three mandatory procedures of the data exchange process: classification, interpretation and automation (Figure 2).

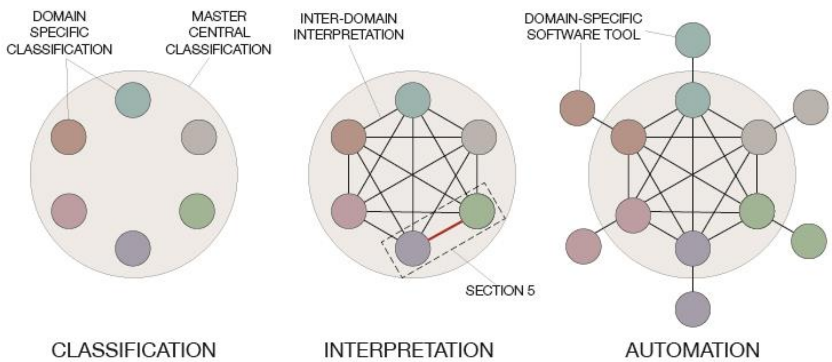


Figure 2 Framework overview

These terms will be explained more thoroughly in the following:

Classification: a data exchange procedure where the systems of terms are developed for all partaking domains and master central classification as their union. These systems include all building elements, attributes, properties and containers used in the exchange processes. Terms originate from the concept system that encompasses the whole AEC industry. The concept system is the knowledge domain that is not limited to a single domain. Different terms may represent the same element, however not within the same domain. The relations between the elements need to be based on the interdisciplinary knowledge. Eventually, the exchange requirements of all domains partaking in the planning process should be supported.

Technological solution on how the classification systems are created and maintained is not the main topic of this research. In this work, the classification systems are defined with the semi-structured database MongoDB, leaving sufficient flexibility for extensions. Current strivings in technological implementation of the AEC classification systems and the relationships between the terms are focused on the ontologies. Proposals involve transition from the monolithic integrated building data models to multiple ontology-based graph data models (Lee et al., 2014; Pauwels et al., 2017; Rezgui et al., 2011).

This approach will be further investigated; however, it is still necessary to facilitate the interpretation of both geometrical and non-geometrical data. The non-geometrical data defined through ontologies has advantages that many interpretations could be defined within the ontology. However, the geometrical interpretations still cannot be defined solely with the ontological relations.

We propose a consistent and clearly structured geometrical representation on the central storage defining every element having the geometrical properties. This has not been possible so far since the practices with the IFC are defined with the STEP (STandard for the Exchange of Product model data), where the geometry parameters are highly interrelated within a schema and the geometry manipulations by the end users are not supported. Therefore, we propose the use of geometry kernels on the central storage to define and store geometrical information required for the exchange. Achieving the interoperability through geometry kernels would ease the development of intermediary software tools.

Interpretation: in this data exchange procedure, the differences between the centrally available information and the domain-specific models are overcome; the domain-specific model is prepared for the import in the software tool. The interpretations might differ depending on the domain and the central model (model which is used as a source of information). The standards are heterogeneous on national and even company levels, and they do not suffice for the automation of interpretation steps between the domains. In the next section we will describe a framework that could be used for the open interdisciplinary interpretation. The proposed interpretation framework consists of validation, filtering, non-geometrical interpretations, geometrical operations, enrichment and reasoning operations.

Automation: this procedure is the technological implementation of the two previously described procedures with the appropriate system architecture. In this way, classification and interpretation are implemented with the software tools, and the central open system is coupled with the AEC software tools (mapping). The classification and interpretation are transparent, in order to support the necessary changes and the heterogeneous workflows, and also to leave the insight and control in the whole exchange process to the end user. The interfaces and the automated methods need to provide a certain amount of flexibility because of the varying workflows and processes in the industry. The main advantage of the centrally interpreted domain-specific models is that the mapping processes between a domain-specific open model and a native building model are reduced to establishing relationships with already prepared domain specific data, and free software developers from complex or reasoning tasks.

In the next section we will focus on the interpretation procedural steps and geometric interpretation methods that are part of the interpretation framework.

5. Interpretation Framework

5.1 Procedural Steps

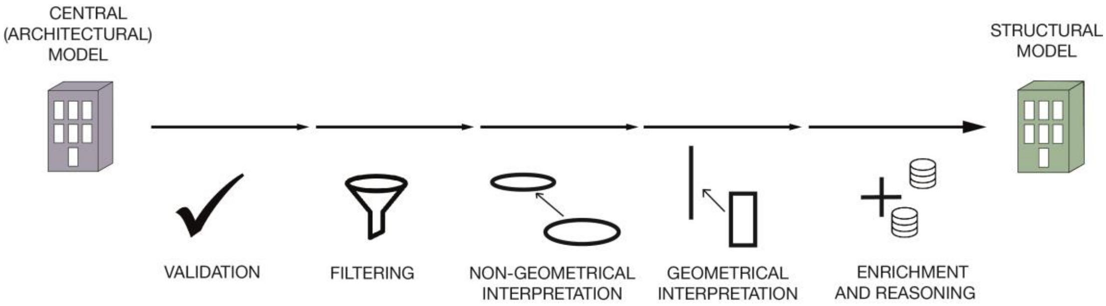


Figure 3 Procedural steps for interpretation

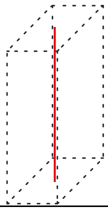
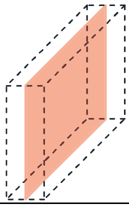
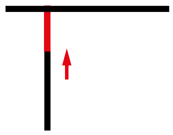
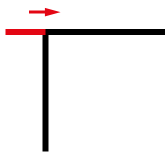
The interpretation procedure to define a structural model from a central data model involves the following procedural steps (Figure 3):

- **Validation:** Identifying the terms available in the central data model, if the elements of the model contain all necessary properties, relations, etc. to allow for the creation of the structural model. The validation is performed on the specific elements or the group of elements within the central model. The validation steps can be so implemented that they automatically report the inconsistencies to the stakeholder who generated specific information. A geometrical element validation can also be introduced. In the case of linear and planar elements, linear elements are considered the ones where two dimensions are considerably larger than the third one ($w<<l$) and ($h<<l$) (Schuler 2016). Further on, a planar element has one dimension considerably smaller than the other two ($t<<l_1$, l_2). The difference between the column and the wall is described as the ($h/b>5$) (Pech & Kolbitsch, 2005) in the case of the concrete and reinforced concrete walls.
- **Filtering:** the elements and properties identified in the validation step on the central storage are reduced to the information required for the next domain-specific planning task. In the case of structural analysis, the load-bearing properties of building elements have been analysed to isolate only the building elements relevant for structural analysis.
- **Non-geometrical interpretation:** Mostly ontological data interpretation. We observed three building elements: wall, column and slab. Since the original model is the architectural model, the 3D physical representation was considered as a starting definition of the element. The structural analysis building elements classes can be identified solely based on the available architectural classification: column is a linear element; wall is a planar element and slab is a planar element.
- **Geometrical interpretation:** geometrical interpretation for this data exchange are complex and described in the next part of this section.
- **Enrichment and reasoning:** adding new information based on the existing ones by using the external databases or methods which can enrich the existing elements with additional knowledge, for instance recognition of the architectural and assigning a structural material.

5.2 Geometric Interpretation Methods

The following geometry interpretation methods are proposed based on the practices employed by structural engineers, modelling instructions and the state-of-the-art review.

Table 1 Geometrical interpretation methods

Method	Description
Linearisation	 Architectural columns are interpreted as linear elements. In this method the central points defining lowest and highest surface of the element are connected and the linear element is created. The cross section information becomes a property of the linear analytical element.
Planarisation	 Filtered planar elements are identified, the largest surfaces are identified and placed in the central position between them. The thickness information becomes a non-geometrical property of the planar analytical element.
Vertical connectivity adjustment	 Vertical connectivity adjustment: in order to be able to transfer the forces, the horizontal elements must be connected to the vertical ones transferring the forces to the ground. Therefore, the linear and planar elements are tested for their connectivity with the native horizontal 3D elements. Tolerances may be introduced as well. The connected elements are extended to the corresponding interpreted horizontal elements.
Horizontal connectivity adjustment	 a) Vertical planar elements need to be checked for horizontal connections in the physical 3D model, then connected in the analytical model. Horizontal connections of vertical linear elements are important for the next step of horizontal element adjustment. b) The edges of the planar horizontal elements need to be aligned with the vertical linear and planar elements. First the vertical elements (or connections of linear vertical elements) located under the horizontal element closest to the edges need to be identified. After testing if the distances are in the tolerance scale the edges are aligned to the vertical elements.

6. System Architecture Proposal

The above described framework has not yet been implemented in any available software tool or the combination of software tools in such a way that the interpretations are open to the end user. Therefore, the implementation of the proposed framework took place by developing a new system architecture. In order to implement the previously defined procedures, a combination of software tools has been established. First, a central storage database was chosen, which replaced the file-based building data, so a synchronous exchange could be achieved. For the data storage a semi-structured database MongoDB was chosen. The advantage of the semi-structured database to a relational database is the flexibility it provides to support unexpected information (Lee et al., 2014; Rasys et al., 2014). The unpredictable behaviour of the end users, the domains that are part of the planning process, as well as the software tools which can be involved differ from project to project (Holzer, 2007) make the flexibility an important factor when choosing a database.

The interpretation framework was implemented with C#, but the chosen semi-structured database can be accessed with other programing languages. The validation, filtering, geometrical and non-geometrical interpretation and enrichment procedural steps can all be practically realized with C#. Mapping processes depend on the API (Application Programming Interface) of the importing software tool, and in the case of Dlubal RFEM, the mapping processes are also supported by C#. For the geometrical interpretation an open geometry kernel OpenCascade was used. In this way, the complex geometry editing methods are simplified with the predefined options provided by the OpenCascade kernel. OpenCascade was used with C# Wrapper, because it is a kernel whose methods are C++ based.

A test workflow (Figure 4) showed promising results for the wider implementation. The starting point was the prepared architectural model on the semi-structured database. The architectural model is created from the Revit IFC export, and converted to JSON (JavaScript Object Notation) format to serve the new workflow. The validation step was not performed since the IFC model was converted and filtered to the desired model in JSON format, providing a valid starting open architectural model for further actions on central database. The interpretation followed the creation of the central open model and the structural analysis model was created on the central database. The process is fully automated, involving geometric and non-geometric information, and enrichment and reasoning. However, it is necessary to support more user-friendly end-user interface in the future. The created model is then mapped to the structural analysis software tool for test purposes.

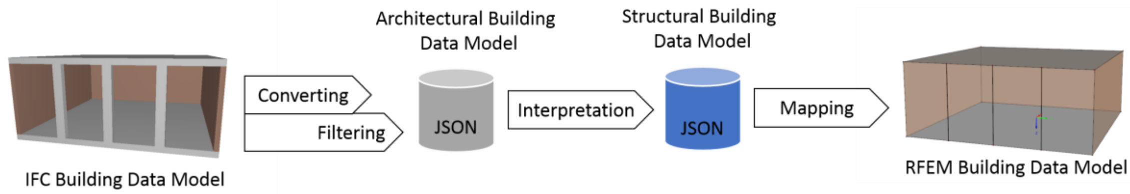


Figure 4 Interpretation framework testing methodology with screenshots

7. Conclusion

This paper describes the proposal of a new framework for overcoming the semantic and geometric differences between the architectural and structural analysis models. Three procedures are recognised as the requirements of an automated exchange framework: classification, interpretation and automation. The focus of the paper is the interpretation procedure taking place on the central data storage.

Interpretation taking place between architectural and structural analysis models can be divided into five procedural steps: validation of the central model, filtering of required elements, interpretation of geometrical and non-geometrical elements and the enrichment and reasoning. The central building model needs to support all of these steps in order to achieve a seamless exchange. A precondition for it is a domain-specific classification.

The greatest challenge for the data exchange between architectural and structural analysis models are the geometrical interpretations. They consist of reduction of dimensionality of linear elements, reduction of dimensionality of planar element, adjustment of connectivity of vertical elements and adjustment of connectivity of horizontal elements. These proposed methods cover some of the most repetitive tasks when the structural model is created, however they do not suffice for all building elements, geometries or materials and would have to be extended for more complex building models.

The test case is limited to a simple building model. The interpretation tasks are implemented with the focus on geometry interpretation methods and used with a test model. System architecture consists of a semi-structured database for central storage, programing language and geometry kernel. The framework implementation should be improved with a more user-friendly interface and allow for more flexibility. The system architecture proposal leaves the interpretation as well as central model open for the end user. The following technical improvements could be considered in the future: the semi-structured database could be replaced with graph database, other programming languages or the geometry kernel with additional methods and geometry definitions could be used. The technical optimisation is not the topic of the work and will be considered in the future research.

Next steps will involve the proof of concept testing that will encompass additional building elements and extend the existing interpretations methods. The technical improvements of system architecture are going to be considered as well.

Acknowledgements

This work was conducted as part of the Doctoral College “Computational Design” on TU Wien (TUW) and the project DATAFILTER in cooperation with Strabag AG. The authors wish to express their appreciation to Dr. Wendelin Sprenger and Theodor Sansakrit Strohal for their support and contribution to the study on the side of Strabag AG.

References

buildingSMART (2019) *International home of openBIM*. Retrieved from http://www.buildingsmart-tech.org

Deng, X. Y., & Chang, T.-Y. P. (2006, June). *Creating Structural Model from IFC-based Architectural Model*. Paper presented at the Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montréal, Canada. Retrieved from http://itc.scix.net/data/works/att/w78-2006-tf577.pdf

DIN - Deutsches Institut für Normung. (2002). *Tragwerke aus Beton, Stahlbeton und Spannbeton - Teil 1: Bemessung und Konstruktion* (DIN 1045-1:2002-07). Retrieved from https://www.umwelt-online.de/recht/bau/din/1045_1ges.htm

Holzer D., Tengono Y., & Downing S. (2007). Developing a Framework for Linking Design Intelligence from Multiple Professions in the AEC Industry. In: Dong A., Moere A.V., & Gero J.S. (Eds.), *Computer-Aided Architectural Design Futures (CAADFutures) 2007* (pp. 303-316). Dordrecht, Netherlands: Springer.

Hu, Z. Z., Zhang, X. Y., Wang, H. W., & Kassem, M. (2016). Improving interoperability between architectural and structural design models: An industry foundation classes based approach with web-based tools. *Automation in Construction, 66*, 29-42. https://doi.org/10.1016/j.autcon.2016.02.001

Lee, J., & Jeong, Y. (2012). User-centric knowledge representations based on ontology for AEC design collaboration. *Computer-Aided Design, 44*, 735-748. doi:10.1016/j.cad.2012.03.011

Lee, J., Jeong, Y., Oh, M., & Hong, S.W. (2014). A Filter-Mediated Communication Model for Design Collaboration in Building Construction. *The Scientific World Journal, 2014*. http://dx.doi.org/10.1155/2014/808613

Liu, Z.-Q., Li, Y.-G., & Zhang, H.-I. (2010). IFC-based integration tool for supporting information exchange from architectural model to structural model, *Journal of Central South University of Technology, 17 (no. 6)*, 1344-1350. https://doi.org/10.1007/s11771-010-0640-z

Mora, R., Bedard, C., & Rivard, H. (2008). A geometric modelling framework for conceptual structural design from early digital architectural models. *Advanced Engineering Informatics, 22*, 254-270. doi:10.1016/j.aei.2007.03.003

Pauwels, P., Zhang, S., & Lee, Y.-C. (2017) Semantic web technologies in AEC industry: A literatur overview. *Automation in Construction, 73*, 145-165. http://dx.doi.org/10.1016/j.autcon.2016.10.003

Pech, A., & Kolbitsch, A. (2005). *Wände*. Wien, Austria: Springer-Verlag Wien

Qin, L., Deng, X.-Y., & Liu, X.-L. (2011). Industry foundation classes based integration of architectural design and structural analysis. *Journal of Shanghai Jiaotong University (Science), 16 (no. 1)*, 83-90. https://doi.org/10.1007/s12204-011-1099-2

Ramaji, I.J. & Memari, A.M. (2018). Interpretation of structural analytical models from the coordination view in building information models. *Automation in Construction, 90*, 117-133 https://doi.org/10.1016/j.autcon.2018.02.025

Rasys, E., Hodds, M., Dawood, N. & Kassem, M. (2014). A Web3d Enabled Information Integration Framework for Facility Management, *Australasian Journal of Construction Economics and Building Conference Series, 2(no. 1)*, 1-12. https://doi.org/10.5130/ajceb-cs.v2i1.3763

Rezgui, Y., Boddy, S., Wetherill, M., & Cooper, G. (2011). Past, present and future of information and knowledge sharing in the construction industry: Towards semantic service-based e-construction?. *Computer-Aided Design, 43*, 502-515. doi:10.1016/j.cad.2009.06.005

Rezgui, Y., Hopfe, C.J., & Vorakulpipat, C. (2010). Generations of knowledge management in the architecture, engineering and construction industry: An evolutionary perspective. *Advanced Engineering Informatics, 24*, 219-228. doi:10.1016/j.aei.2009.12.001

Romberg, R., Niggl, A., van Treeck, C., & Rank, E. (2004, June). *Structural Analysis based on the Product Model Standard IFC*. Paper presented at the 10. International Conference on Computing in Civil and Building Engineering (ICCCBE), Weimar, Germany. https://doi.org/10.25643/bauhaus-universitaet.243

Schuler, E. (2016). *Tragwerkslehre 3 - Tragwerkselemente*. Vaduz, Liechtenstein: Universität Liechtenstein. Retrieved from http://www.gbd.at/skripten/TWL3.pdf

Sibenik G. (2016). Building information modelling based interdisciplinary data exchange: a case study. In J. Underwood, B. Kumar, & F. Khosrowshahi (Eds.), *Proceedings of 1st International UK BIM Academic Forum Conference* (pp. 379-90). Glasgow, UK: Glasgow Caledonian University.

Sibenik G. & Kovacic I. (2019, June). *Proposal for a classification system supporting interdisciplinary model exchange between architecture and structural analysis*. Paper presented at the conference CIB World Building Congress 2019 ‘Constructing Smart Cities’, Hong Kong, China.

Wan, C., Chen, P.-H., & Tiong, R. L. K. (2004). Assessment of IFCs for Structural Analysis Domain. *ITcon, 9*, 75-95. Retrieved from https://www.itcon.org/paper/2004/5

Wang, X., Cui, Z. P., Zhang Q. L., & Yang, H. Z. (2013). Creating Structural Analysis Model from IFC-Based Structural Model, *Advanced Materials Research*, *Vols. 712-715*, 901-904. https://doi.org/10.4028/www.scientific.net/AMR.712-715.901

Weise, M., Katranuschkov, P., Liebich, T., & Scherer, R. J. (2003). Structural analysis extension of the IFC modelling framework. *Electronic Journal of Information Technology in Construction, 8*, 75-95. Retrieved from https://www.itcon.org/paper/2003/14

Zhang, X.-Y., Hu, Z.-Z., Wang, H.-W., & Kassem, M. (2014). An Industry Foundation Classes (IFC) Web-Based Approach and Platform for Bi-Directional Conversion of Structural Analysis Models. In I. I. Raymond, & I. Flood (Eds.), *Proceedings of the 2014 International Conference on Computing in Civil and Building Engineering* (pp. 390-397). Orlando, USA: American Society of Civil Engineers (ASCE). https://doi.org/10.1061/9780784413616.049

A Workflow Model for Setup and Maintenance of an Integrated Building Model for Energy Management

Maryam Montazer[1, *], Georg Suter[2], Filip Petrushevski[3], Milos Sipetic[3], Max Blöchle[3], Stefan Gaida[4], Wolfgang Kastner[4] and Christian Schiefer[5]
[2]TU Wien, Design Computing Group, Vienna, Austria
[3]AIT Austrian Institute of Technology, Vienna, Austria,
[4]TU Wien, Automation Systems Group, Vienna, Austria
[5]Caverion Austria, Vienna, Austria
[*]email: maryam.montazer@tuwien.ac.at

Abstract

Building automation systems (BAS) are responsible for control, monitoring and supervision of building services, such as heating, ventilation, air conditioning (HVAC), and lighting. The objectives of building automation are energy-efficient operation of building systems in a secure and safe manner while providing thermal and visual comfort, and enhanced life cycle of utilities. As building blocks of BAS, sensors installed in a building typically create large amounts of data during the operation phase. These data provide a basis for improved building energy management. Statistical processing and, more recently, machine learning have been used to interpret sensor data. However, improved reporting and visualization of energy and comfort related parameters in the building operation phase, which are optimized for human interpretation, are relevant to support complementary data analysis by humans. Towards this end, models that combine building information model (BIM) with runtime data from a building energy management system (BEMS) could provide a useful basis. In this paper, we describe workflows for the setup and maintenance of such an integrated building model. Both workflows are developed based on process engineering principles. Tasks in the model setup workflow are tested in an existing medium-size office building. Data modeling and processing issues encountered during testing are described.

Keywords: BIM, BEMS, workflow modeling

1. Introduction

Energy consumption of buildings comprises 40% of total energy use in the European Union. The contribution of building services, especially heating, ventilation, and air conditioning (HVAC) systems, accounts for 50% of energy use in buildings and 20% of total global energy use (Perez-Lombard, Ortiz & Pout, 2008). Building Energy Management Systems (BEMS) are software systems to supervise and control HVAC and systems of the electrical installation domain. They provide thermal and visual comfort to occupants. These services should be provided in an energy effective way. BEMS must respond to dynamic outdoor conditions, take into account a building's spatial structure, building materials, as well as occupant behavior. A fundamental challenge in BEMS is the accurate interpretation of large quantities of data generated by sensors and actuators about conditions in a building to detect defects that may cause inadequate indoor environment quality and/or energy ineffectiveness. Although statistics and machine learning methods have been applied to interpret the generated data (Ahmad, Chen, Guo & Wang, 2018), in situations where such methods are unable to detect defects with sufficient accuracy, human data analysis is still necessary. Of particular interest are information visualization and visual analytics methods to support data analysis (Munzner, 2014). A building model that integrates BEMS data could provide a useful basis for effective human analysis of BEMS data. For example, visualizations of sensor data in their spatial context could be derived from such an integrated building model to help facility managers identify spaces with inadequate thermal conditions (Petrushevski et al., 2018). In this paper, we propose workflows for the setup and maintenance of such an integrated building model.

2. Related work

A BEMS is a system that monitors and controls energy-related systems from mechanical and electrical equipment in buildings (Sayed & Gabbar, 2018). It is responsible for managing energy supply, storage, distribution, and consumption. BEMS focus on preferably low building energy consumption or reduced energy costs as well as a small or minimized deviation from the intended user comfort in the building. Related automation functionality includes power-saving operation, like optimum start and stop control of air-conditioning equipment during non-office hours, adjusted for system inertia. Monitoring and controlling of energy-related systems produce large amounts of data which makes it difficult to extract relevant information for building operation optimization. Hence, methods such as neural networks, fuzzy logic, or evolutionary algorithms can be applied to improve energy management in buildings (Manic, Wijayasekara, Amarasinghe &Rodriguez-Andina, 2016). Molina-Solana, Ros, Ruiz, Gomez-Romero and Martin-Bautis (2017) discuss various use cases for the application of machine learning algorithms on BEMS data. Among others, these include prediction of building energy load, fault detection and prevention, and economic analysis of electric consumption. Trends like Internet of Energy (Vu, Le & Jang, 2018) and fog computing (Shen et al., 2018) are expected to play an important role in future BEMS. Several studies address the integration of BIM and BEMS to optimize building energy use. To improve the operational inefficiencies in the buildings, Tang, Shelden, Eastman and Pishdad-Bozorgi (2019) investigate the integration of BIM and real-time data. Dong, O'Neill and Li (2014) describe a BIM-based database for fault detection and diagnostics (FDD) which facilitates information exchange between static and dynamic real-time operational data sources. The integration of static and dynamic information requires significant manual modeling effort. McGlinn, Yuce, Wicaksono, Howell and Rezgui (2017) propose an intelligent monitoring interface for energy management which formed part of a BEMS. They use BIM and semantic web technologies to integrate static and runtime sensor data to generate rules for building management. Zhong, Gan, Luo and Xing (2018) proposed an ontology-based framework for monitoring indoor air quality, thermal and humidity conditions of a building via integration of BIM and retrieved sensor information with semantic web technologies. Prouzeau et al. (2018) have developed a prototype of a building management system (BMS) that uses visual analytics to provide insight into energy efficiency and comfort in buildings. Gerrish et al. (2017) identify the challenges and potential of applying BIM to building energy performance visualization and management. Data management between design, construction and operation is seen as a key challenge. Autodesk Dasher is a building performance visualization system that displays historical and real-time sensor data in a building model (Hailemariam et al., 2010). Although significant work has been done in visualization and reporting of energy and comfort related parameters, the tasks to setup and maintain integrated building models to support such analysis have not yet been described in detail.

3. Methodology

Workflow models for the setup and maintenance of an integrated building model are proposed. A workflow model formally represents the flow of required activities in a process and their logical sequence (Sommerville, 2011). The workflow models are structured according to five phases in software engineering. In the first *requirement engineering* step, stakeholders and engineers define the system and the constraints for its operation. In *system design*, the overall system architecture is specified. In *system implementation*, modules are implemented and integrated to make the system operational. In *system validation*, the system is checked against stakeholder requirements. In *system evolution*, the system is modified to reflect changing customer requirements or updates. The software engineering phases corresponding to key tasks in the proposed workflow models are shown in

Figure 1.

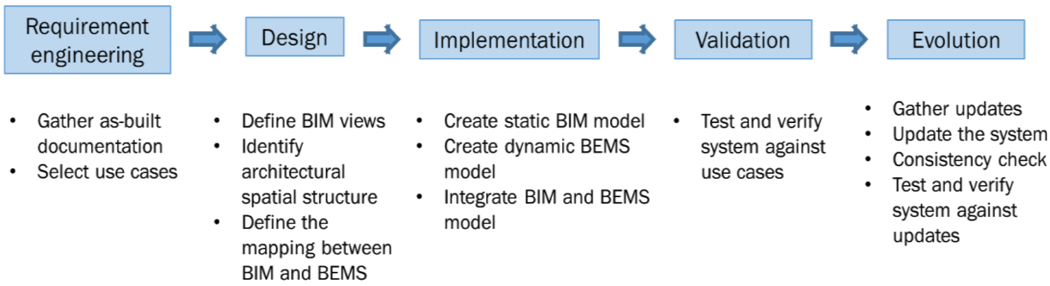


Figure 1: Software engineering phases (Sommerville, 2011) and key tasks in the setup and maintenance of the integrated building model.

The workflow models are represented in the business process modeling notation (BPMN) (Object Management Group [OMG], 2011). Roles and activities in the models are defined based on qualitative interviews with stakeholders and use cases developed in previous work (Petrushevski et al., 2018). A subset of the tasks in the model setup workflow are tested for an existing, medium-size office building. Testing of all tasks is currently infeasible because the integrated building model is still under development. Data modeling and processing challenges arising during testing are described.

4. Model setup workflow

4.1 Actors

Five actors are identified for the model setup workflow (Figure 2). The facility manager (FM) is the end user of the visualization and reporting system and is involved in the setup and maintenance of the integrated building model. He provides as-is information about the building and its BEMS and validates requirements. The BIM modeler is responsible for defining, designing and modeling the building model. He is familiar with the IFC data model. The BEMS modeler is responsible for storing, retrieving and modelling the operational building data. He is experienced with BEMS systems design and operation. The system integrator is responsible for the interoperability between static and dynamic building data and the deployment of the integrated building model.

4.2 Modeling requirements

The initial task in the modeling requirements phase is to gather as-is documentation about the building and its BEMS. Collaboration of multiple actors is necessary to achieve a detailed understanding of a building's condition. This includes determining space layout and usage as well as BEMS components at plant and zone levels. Based on available documentation, use cases for visualizing and reporting energy of comfort related parameters are selected by the actors. Six use cases have been defined in previous work (Petrushevski, et al., 2018). They include visualization of data point (e.g. temperature sensor or set point) values, alarms, preprocessed data, logging data, and energy consumption reporting. The FM validates modeling requirements.

4.3 Definition of model structure

The BIM modeler defines the structure for the integrated building model. A model structure consists of one or more views. A view corresponds to the objects (e.g. rooms, windows, temperature sensors, and HVAC terminals) that are modeled and how they are spatially related. The latter includes defining the spatial structure. A building is decomposed into spatial structure elements, such as sections, zones, floors, and rooms. It is common practice for BEMS data point names to include references to spatial structure elements (Balaji et al., 2016). Dependent on selected use cases, an integrated model may need to support multiple views and hence multiple spatial structures. For example, thermal zones are useful to visualize indoor air data points. A thermal zone is a group of rooms with similar thermal loads that are controlled together. In a corresponding spatial structure, a building may be divided into sections, floors, thermal zones, and rooms. Spatial structures are initially identified separately by BIM and BEMS modelers. The BEMS modeler selects data points that are to be included in the integrated building model. If applicable, additional sensors, such as data loggers or meters, are installed on site. Differences between spatial structures for BIM and BEMS need to be reconciled. These occur when different conceptual models, naming schemes, or identifiers are used. Hence mappings must be defined for objects that are included in BIM and BEMS models.

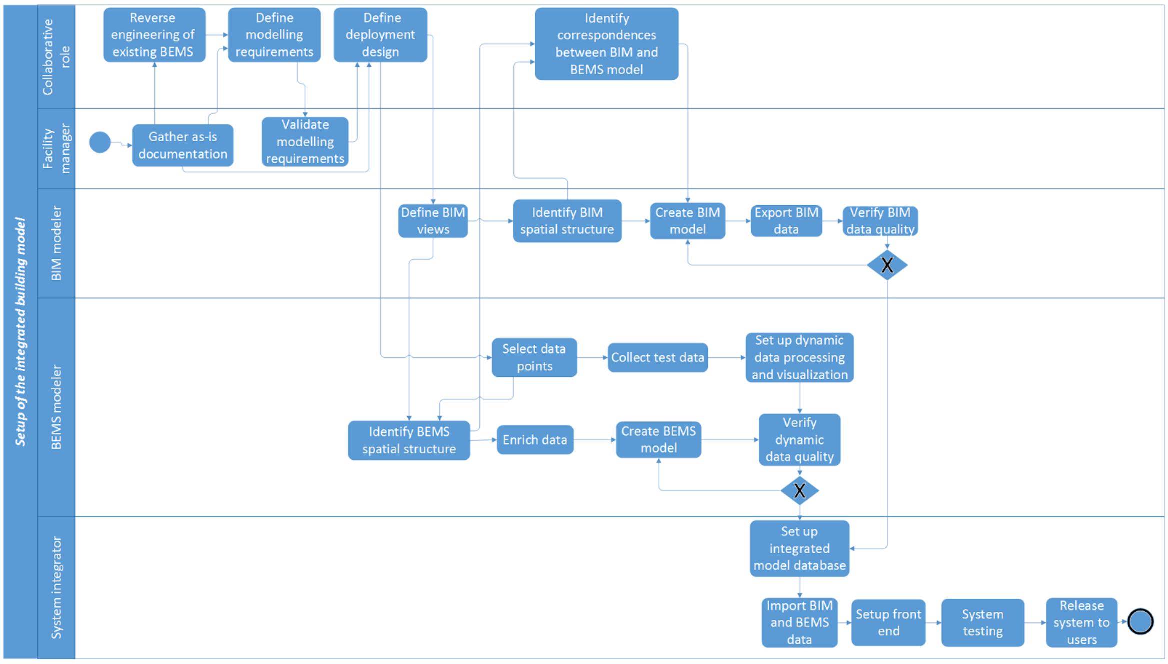


Figure 2: Workflow for the setup of the integrated building model.

4.4 Creation of BIM and BEMS models

Based on the model structure, the BIM modeler creates a building model using a BIM authoring system. The building model includes semantic and geometric object data as well as spatial relationships between objects. The building model is exported from the BIM authoring system using the IFC format (buildingSmart, 2019). This format is chosen because it is vendor neutral, information rich, and supported by many BIM authoring systems. Among available IFC model view definitions (MVDs), the IFC Coordination View Version 2.0 is a widely supported MVD. BEMS specific data, e.g. about devices, may need be exported via custom property sets since coverage of such data in the current IFC release 2x4 is limited. To facilitate updates of the integrated model database, the IfcGUID property must be populated. IfcGUID is a globally unique identifier for IFC objects. In addition to creating the BIM model, the BIM modeler is responsible for verifying its data quality. This can be done with IFC viewing tools or checking systems (e.g., Solibri, 2019).

In parallel to the creation of the BIM model, available information from the BEMS is processed by the BEMS modeler. A list of all data points is prepared. This list can be created automatically for most systems. Often it is necessary to manually enrich the data with additional semantics. Typically, the type of the data point, e.g. temperature sensor reading, and its unit of measurement need to be determined. Next, each point in the list is mapped to a device in the BIM model. Actual time series data are recorded and stored in a database. Time series data must be checked for consistency regarding range and continuity. The installation of additional external sensors may be necessary, for example, to measure temperature, humidity, or air quality at locations where there are no existing sensors. Semantics must be defined for these sensors as well. Finally, the enriched data point list is converted into a machine readable format, such as Comma Separated Values (CSV), JavaScript Object Notation (JSON), or Extensible Markup Language (XML).

4.5 Setup of integrated model database

The fundamental component of the integrated model database is a knowledge base based on well-known ontologies, such as ifcOWL (Beetz, Van Leeuwen, & De Vries (2009)), Brick (Balaji et al., 2016), and BOT (Rasmussen et al., 2017). The knowledge base is complemented by a time series database for sensor readings as well as current and historic set points. The initial step of setting up the integrated model database is to convert the IFC model created by the BIM modeler into ifcOWL. The output of this conversion is imported into the knowledge base. Additional information, such as adjacencies and positions of devices, which are not explicitly available in ifcOWL, are calculated by appropriate tools and integrated into the knowledge base by using concepts and relations of Brick and BOT. Data points as well as the corresponding time series data are integrated by importing the previously created machine readable list of data points. Data from the list are converted into triples which can be stored in the knowledge base. The result is a common database that comprises BIM data, additional explicit location information, data point descriptions, and references to time series data. Information from this integrated model database can be retrieved via a high-level Application Programming Interface (API) or a query language, such as SPARQL. Finally, the system is tested against functional and non-functional requirements and released to users.

5. Model maintenance workflow

The maintenance workflow model involves updating the integrated building model during operation (Figure 3). Examples for updates are the refurbishment of spaces, or the replacement of sensors. Typically, updates are local and do not significantly affect the model structure. Compared with the model setup workflow, the model maintenance workflow consists of fewer but similar tasks. Nonetheless, updates may involve multiple actors. BIM and BEMS modelers need to verify data quality of their changes before the integrated model is updated.

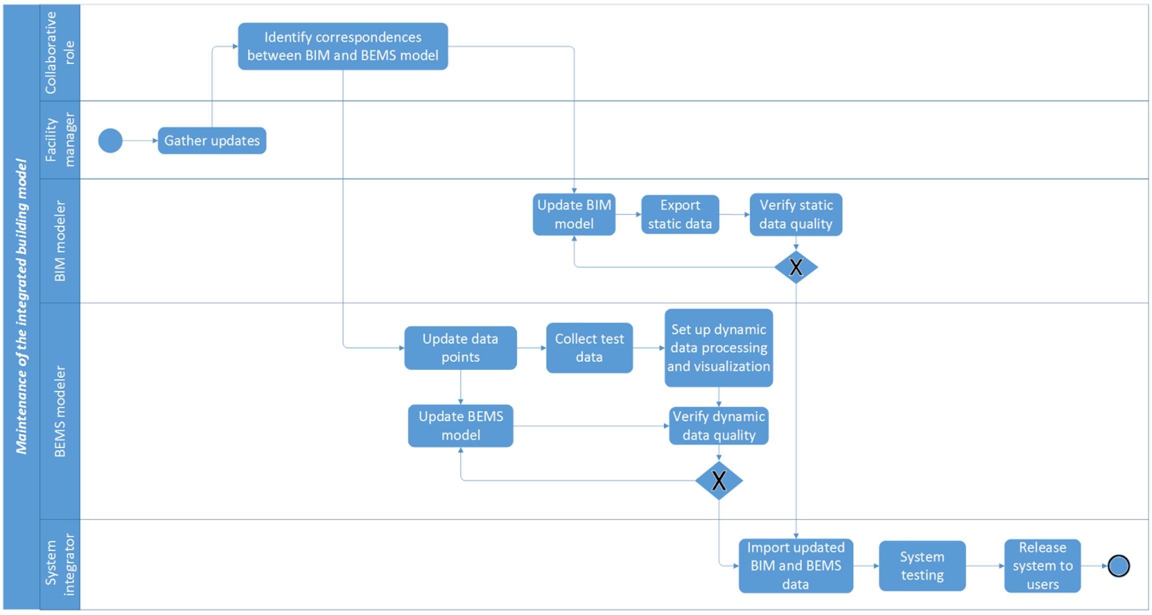


Figure 3: Workflow for the maintenance of the integrated building model.

6. Workflow testing

Tasks in the model setup workflow are executed to create an integrated building model for a test building. The latter is a five-story, medium size office building located in suburban Vienna, Austria. The building is typical for office buildings built in the 1970s and 1980s in Western Europe. The L-shaped building consists of two sections facing East, South, and North.

6.1 Modelling requirements

The as-is documentation of the building consists of 2D vector drawings and spreadsheets for space use, fire safety, air inlets/outlets, and fan coils. A comprehensive written documentation about the as-is BEMS does not exist. Instead, there are HVAC schemes of the building and a list of datapoint descriptions. The rest of the information was obtained through reverse engineering and meetings with responsible building technicians and specialists. The building has three thermal zones: one for each section and one for a meeting room. Each zone is served by a plant that provides a constant volume of heated/cooled air to ensure minimum air change. Spaces are further heated or cooled with fan coils. Unfortunately, no data about their state is available in the BEMS.

Based on the as-is documentation, the use case ‘Visualization of logging data in a spatial context’ was selected to derive modeling requirements (Petrushevski, et al., 2018). In this use case, external sensors are installed to collect data about indoor thermal and air quality conditions, e.g. in locations where there no existing sensors. Required information includes logger locations and readings. The spatial context is modeled by architectural element (space, door, window) and HVAC terminal (e.g. air inlet/outlet) geometries. Space function data are required because they are useful to analyze logger readings. In addition to the containment relationship between loggers and spaces, the space adjacency relationship is required to visualize differences in logger readings between adjacent spaces.

6.2 Definition of model structure

As only one use case was selected, the model structure has a single view which consists of data loggers and their spatial context, as represented by architectural elements (spaces, windows, and doors) and HVAC terminals. In the spatial structure, the building has two sections, and each section has five floors. Thermal zones were not modeled explicitly. Identifying correspondences between the building model and data loggers was a major modeling challenge. This is because object properties in the integrated model database originate in multiple systems which assign different object identifiers. This raises the issue of preserving object consistency when object properties are modified in any system. For example, locations of data loggers are modeled in a BIM authoring system, and logger readings in a time series database. Data loggers are identified in the BIM authoring system by native identifiers and IfcGUIDs. In the time series database, on the other hand, data loggers are identified by their manufacturing identifier. These identifiers were mapped manually map to ensure consistency.

6.3 Creation of BIM and BEMS models

As the documentation of the test building consisted of unstructured data, it was necessary to create the BIM model from scratch. This was done using the Revit Architectural BIM authoring software (Autodesk 2019a). The BIM model was exported to an IFC file. The file content was visualized in a viewing software to verify its correctness and completeness for the selected use case (Solibri, 2019). In general, the IFC data exported from Revit Architectural was found to be complete and accurate. A limitation concerns the adjacency relationship between spaces, which is required to derive temperature differences between adjacent spaces. This relationship is not modeled explicitly in the IFC schema. It may be derived from second level space boundaries. However, corresponding second level space boundaries are not linked in the IFC file exported by Revit. Using clash detection algorithms in Solibri Model Checker (SMC) software, it is feasible to derive space adjacency relationships from an IFC model (Solibri, 2019). Unfortunately, it is currently infeasible to export semantically enriched IFC models from SMC. As an alternative, semantic enrichment of the BIM model was investigated using the Space Modeler (SM) system (Suter 2015). The SM system derives and exports the space adjacency relationship as well as other spatial relationships for a given building model. However, it is currently unable to process complete IFC files. As a workaround, the BIM model was exported from Revit in the DWG format. This lead to significant data loss and required data re-entry, e.g. of space geometry data. To summarize, the reuse and semantic enrichment of IFC models exported from a BIM authoring tool for the integrated model database is currently unresolved. A further issue is limited support for modeling space functions in Revit. Offices in the test building have different occupancy types, including team office, open plan office, and private office. Occupancy types were modeled as semantic labels and added to the BIM model using the SM system. The system was further used to define mentioned identifier mappings between BIM and BEMS objects.

In order to obtain a rudimentary list of available data points from the BEMS as well as to collect time series data, an Open Platform Communications (OPC) server was installed in the deployed Programmable Logic Controller (PLC). A script was used to read all 1906 OPC data items from this server. Another script reads and stores the current values from the server in a five minutes cycle. It turned out that extracting information about data point types, locations (references to devices), and units from the available data is challenging and laborious. First, there are many data points in the PLC which are not in use, meaning that the corresponding IO-ports are not wired. Therefore 1368 data points without any value change in four months were deleted from time series data. However, significant manual work is required to select the data items of interest. In this particular case, the only available information about each data point was a name which does not follow a consistent schema. Hence data point types, references to devices, as well as units had to be added manually.

A wireless data logging system was deployed in the test building to gain insights regarding the temperature, humidity and CO2 characteristics of individual offices. Due to its proprietary nature, data is exported from the system as CSV files that are imported into the time series database at regular intervals. Data collected by the system are verified by visualization in their spatial context. This is illustrated with a temperature data sample for the second floor of the test building (Figure 4). For the temperature data sample, the visualization reveals that most South-facing offices are overheating in the afternoon, while North-facing ones are in the comfort temperature range. The visualization supports the conclusion that the data sample is sensible.

Figure 4: Verification of dynamic data quality by visualization of a temperature data sample collected by data loggers on the second floor of the test building using the Space Modeler system (unit: ^oC).

6.4 Setup of integrated model database

For the integration of data from BIM and BEMS models, a container-based infrastructure was set up. Services for storage, interfaces, and security are provided in the form of Docker containers. Apache Jena components TDB (triple store) and Fuseki (SPARQL server) are used to store and provide the modeled semantic building information in a knowledge base. The time series database InfluxDB was installed to host time series data for available data points. High-level access to all this information is provided by a Representational State Transfer (REST) API implemented in ASP.NET Core. This allows users who are not familiar with semantic web technologies to gain data from the integrated model database without writing SPARQL queries.

The BIM model was converted to ifcOWL utilizing the Java-based IFCtoRDF tool. Subsequently, ontologies which are required to represent all aspects of BIM and BEMS models are loaded into the knowledge base. These are ifcOWL, Brick (Balaji, et al, 2016), BOT (Rasmussen et al, 2017), and QUDT (QUDT, 2019) for units. Mappings between these ontologies were defined and inserted in the triple store. An example for such a mapping is that an IfcSpace is a subclass of a space in BOT. Based on this mapping, a reasoner is able to assign the BOT space class to all IfcSpace instances. BOT models adjacency relations between spaces, which are not available in ifcOWL. In the following, locations of devices as well as relations between spaces, floors, and building parts were automatically extracted and inserted into the knowledge base from JSON-based outputs of the SM system which were generated in the BIM modeling phase. Finally, the semantically enriched list of data points created by the BEMS modeler was processed. While data points and their assignments to spaces and devices are represented in the knowledge base with concepts provided by the Brick ontology, units are taken from the QUDT ontology. An additional data property is used to specify the name of the corresponding time series in the time series database. Apart from the creation of the knowledge base, collected time series data of six months (February 2018 – June 2018) was imported into the InfluxDB.

The Autodesk Forge platform and Angular web application framework are used as a front-end for interactive, 3D visualization of the integrated building model (Autodesk, 2019b; Angular 2019). The front-end uses the REST API provided by the knowledge base to retrieve time series data from the integrated model database and visualizes them in their spatial context. This is illustrated in Figure 5 for a temperature data sample collected by data loggers in the test building.

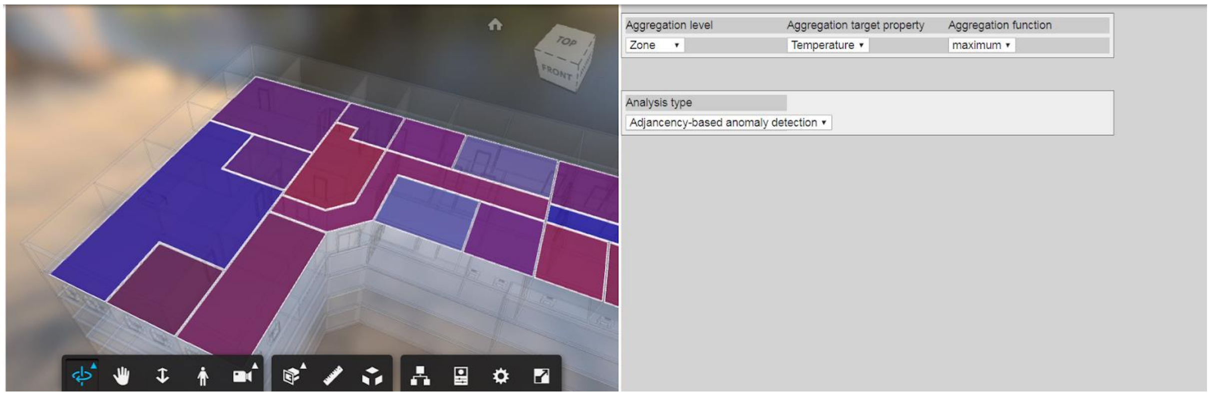


Figure 5: Visualization of temperature data collected by data loggers on the second floor of the test building using the web based front-end application. Temperature data are aggregated at the room level (there may be several sensors in a room) based on maximum readings. Rooms are shaded to highlight those that are considerably hotter (red) or colder (blue) than their adjacent rooms.

6. Conclusion

The work presented in this paper is motivated by the need for improved reporting and visualization of energy and comfort related parameters in the building operation phase. Workflow models for setting up and maintaining an integrated model that supports such visualization and reporting have been proposed. Key tasks in the model setup workflow were tested for a medium-size office building. Several data modeling and processing challenges have been identified. They include incomplete as-is documentation of the BEMS and limited data interoperability. Specifically, the definition of mappings between BIM and BEMS objects that are modeled in different systems was labor-intensive. Automated extraction of semantic information from informal data point descriptions could address this issue. In future work, we plan to further test and evaluate model setup as well as maintenance workflows by deploying and using the integrated building model database in additional test buildings. A cost-benefit analysis will provide more detailed insights into the trade-offs between modeling effort and visualization and reporting capabilities enabled by the integrated building model. We will further investigate how routine model updates, such as the replacement of sensors or actuators, could be automated.

Acknowledgements

This work was funded under the project "Building Information Modeling for Building Energy Management Systems" (BIM4BEMS) by the FFG (Austrian Research Promotion Agency) program City of Tomorrow (project number 854677).

References

Ahmad, T., Chen, H., Guo, Y., & Wang, J. (2018). A comprehensive overview on the data driven and large scale based approaches for forecasting of building energy demand: A review. *Energy and Buildings*, *165*, 301-320.

Angular (2019) [Computer software]. Available from: https://angular.io/

Autodesk Inc. (2019a), Autodesk Revit (Version 2018) [Computer software]. Available from: https://www.autodesk.com/products/revit/overview

Autodesk Inc. (2019b) [Computer software]. Available from: https://forge.autodesk.com/

Balaji, B., Bhattacharya, A., Fierro, G., Gao, J., Gluck, J., Hong, D., ... & Berges, M. (2016). Brick: Towards a unified metadata schema for buildings. In *Proceedings of the 3rd ACM, International Conf. on Systems for Energy-Efficient Built Environments* (pp. 41-50). ACM.

Beetz, J., Van Leeuwen, J., & De Vries, B. (2009). IfcOWL: A case of transforming EXPRESS schemas into ontologies. Ai Edam, 23(1), 89-101.

BuildingSMART International Ltd. (2019). IFC Overview summary. Retrieved from: http://www.buildingsmart-tech.org/specifications/ifc-overview

Dong, B., O'Neill, Z., & Li, Z. (2014). A BIM-enabled information infrastructure for building energy Fault Detection and Diagnostics. Automation in Construction, 44, 197-211.

Gerrish, T., Ruikar, K., Cook, M., Johnson, M., Phillip, M., & Lowry, C. (2017). BIM application to building energy performance visualisation and management: Challenges and potential. Energy and Buildings, 144, 218-228.

Hailemariam, E., Glueck, M., Attar, R., Tessier, A., McCrae, J., & Khan, A. (2010, May). Toward a unified representation system of performance-related data. In Proc. eSim 2010 Conf. IBPSA–Canada eSim Conf (pp. 117-124).

Manic, M., Wijayasekara, D., Amarasinghe, K., & Rodriguez-Andina, J. J. (2016). Building energy management systems: The age of intelligent and adaptive buildings. IEEE Industrial Electronics Magazine, 10(1), 25-39.

McGlinn, K., Yuce, B., Wicaksono, H., Howell, S., & Rezgui, Y. (2017). Usability evaluation of a web-based tool for supporting holistic building energy management. Automation in Construction, 84, 154-165.

Molina-Solana, M., Ros, M., Ruiz, M. D., Gómez-Romero, J., & Martín-Bautista, M. J. (2017). Data science for building energy management: A review. Renewable and Sustainable Energy Reviews, 70, 598-609.

Munzner, T. (2014). Visualization analysis and design. AK Peters/CRC Press.

OMG., Parida, R., & Mahapatra, S. (2011). Business process model and notation (bpmn) version 2.0. Object Management Group.

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. Energy and buildings, 40(3), 394-398.

Petrushevski, F., Montazer, M., Seifried, S., Schiefer, C., Zucker, G., Preindl, T., ... & Kastner, W. (2018). Use Cases for Improved Analysis of Energy and Comfort Related Parameters Based on BIM and BEMS Data. In Workshop of the European Group for Intelligent Computing in Engineering (pp. 391-413). Springer.

Prouzeau, A., Dharshini, M. B., Balasubramaniam, M., Henry, J., Hoang, N., & Dwyer, T. (2018). Visual Analytics for Energy Monitoring in the Context of Building Management. In 2018 International Symposium on Big Data Visual and Immersive Analytics (BDVA) (pp. 1-9). IEEE.

QUDT (2019). QUDT Website. Available from: http://www.qudt.org

Rasmussen, M., Pauwels, P., Lefrançois, M., Schneider, G. F., Hviid, C., & Karlshøj, J. (2017). Recent changes in the building topology ontology. In LDAC2017-5th Linked Data in Architecture and Construction Workshop.

Sayed, K., & Gabbar, H. A. (2018). Building Energy Management Systems (BEMS). Energy Conservation in Residential, Commercial, and Industrial Facilities, 15-81.

Shen, Z., Yokota, K., Jin, J., Tagami, A., & Higashino, T. (2018). In-network self-learning algorithms for BEMS through a collaborative Fog platform. In 2018 IEEE 32nd International Conference on Advanced Information Networking and Applications (AINA) (pp. 1162-1169). IEEE.

Solibri Inc., A Niemetschek Company (2019). Solibri Model Checker (Version 9.8) [Computer Software] Retrieved from: https://www.solibri.com/solibri-model-checker.html.

Sommerville, Ian. (2011). Software Engineering. Ninth edition. Boston: Addison-Wesley.

Suter, G. (2015). Definition of views to generate, visualize, and evaluate multi-view space models of schematic building designs. In Proc. of the 22nd EG-ICE Workshop 2015.

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X. (2019). A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. Automation in Construction, 101, 127-139.

Tomasi, R., Sottile, F., Pastrone, C., Mozumdar, M. M., Osello, A., & Lavagno, L. (2015). Leveraging BIM interoperability for UWB-based WSN planning. IEEE Sensors Journal, 15(10), 5988-5996.

Vu, T. L., Le, N. T., & Jang, Y. M. (2018, October). An Overview of Internet of Energy (IoE) Based Building Energy Management System. In 2018 International Conference on Information and Communication Technology Convergence (ICTC) (pp. 852-855). IEEE.

Wix, J., & Karlshoej, J. (2010). Information delivery manual: Guide to components and development methods. BuildingSMART International, 5(12), 10.

Zhong, B., Gan, C., Luo, H., & Xing, X. (2018). Ontology-based framework for building environmental monitoring and compliance checking under BIM environment. Building and Environment, 141, 127-142

Integrating EVM and ABC for developing risk/rewards sharing metrics of IPD: A web-based management system

Faris Elghaish[1*], Sepehr Abrishami[2], M. Reza Hosseini[3] and Bahareh E. Dehkordi[4]

[1]Ph.D. Researcher at University of Portsmouth
[2]Senior lecturer at University of Portsmouth
[3]Senior Lecturer in Construction at Deakin University
[4]Ph.D. Researcher at City University of London
[*]Email: faris.elghaish@port.ac.uk

Abstract

Integrated Project Delivery (IPD) is highly recommended to be utilised with Building Information Management, particularly, with BIM level 3 implementation process. The literature review survey highlights that there are financial management challenges that face the proposed integration, these challenges are mainly related to the IPD compensation approach, as well as, the conventional cost control approaches that are not consistent with IPD principles. As such, this paper presents an integration of several methods to support automating sharing risk/rewards among project parties, thus, enhancing the relationship among IPD's core team members. Activity Based Costing (ABC) is integrated into Earned Value Management (EVM) to develop mathematical models that can determine the three main IPD financial transactions fairly (reimbursed costs, cost saving and profit), due to ABC abilities to distinguish between direct, indirect and overhead costs precisely. Since IPD's core team members usually receive their profits by the end of the project, regardless of the project timeline, therefore, a data sharing system is highly needed. As such, a web-based management system is developed to display the output of proposed risk/rewards sharing models, as well as, an innovative grid is developed to show the project status graphically to respect the diversity in core team members educational backgrounds. To demonstrate the applicability of the developed system, a real-life case study was used, in which, promising results were collected in regards to visualising the cost control data, and easy understanding of the accumulative status of the project cost and schedule. In addition, the case study shows that the proposed integration of different methods is interoperable and applicable, particularly, BIM and EVM-web system.

Keywords: IPD; BIM; ABC; EVM; Risk/rewards sharing

1. Introduction

Integrated project delivery (IPD) is characterised by the early, collaborative and collective engagement of key stakeholders through all phases of delivering a project (Ahmad et al., 2019). Traditional forms of IPD, such as alliancing, can be implemented without BIM. However, new forms of IPD are defined in relation to their integration with BIM (Rowlinson, 2017) which facilitates smooth data exchange between a project's packages and parties, in line with IPD's aims and objectives (AIA, 2007). The integration of BIM and IPD improves all likely outcomes of the design and construction process, including cost/profit, the schedule, return on investment (RoI), safety, productivity and relationships (Elghaish et al., 2019). Integrated project delivery (IPD) relies on open pricing techniques and fiscal transparency among participants (Ahmad et al., 2019). In addition, project stakeholders, such as designers and contractors, typically assess and determine their profit and shared risks according to the deviation between actual and target costs (AIA, 2007).Successful delivery of a project through IPD is however not easy; IPD requires fulfilling a wide range of requirements (Fischer et al., 2017). Of these requirements, the IPD compensation model, also called risk/reward compensation, is of cardinal importance (Ma et al., 2018). It is described as a key principle of IPD (Zhang et al., 2018), that plays a pivotal role in stimulating creativity, motivating collaboration, and sustaining performance (Zhang and Li, 2014). The risk and reward must be shared and allocated to all participants in core project teams, necessitating joint project control (Fischer et al., 2017). For designing the risk and reward model (hereafter referred to as the compensation approach), economic models provide a sound foundation based on the cost of projects (AIA, 2007).

The cost structure of IPD needs some improvements in order to make sure that there is no profit hidden in the estimated cost (Allison et al., 2018), to achieve the purpose of using IPD to increase the trust among project parties (Ma et al., 2018). Due to risk/rewards are not shared individually for IPD core team members (AIA, 2007, Pishdad-Bozorgi and Srivastava, 2018), therefore, any misleading in determining the individual trade package, will affect the value of the proportions of profit-at-risk percentage of each member in IPD team. One of the main principle of IPD, the allocation of Parties' profits defer to the end of the project, therefore, this represents a challenges to speed the implementation of the IPD since this requires all members to attend all meetings even if their works are completed at earlier (Roy et al., 2018). As such, using Information Technology (IT) is important to share the information among parties regardless of their geographical places.

A review of the literature shows several trends of research on the topic. Of these, a major part of the research has been allocated to exploring the potential of available tools and techniques (i.e. EVM and ABC within IPD) (Hosseini et al., 2018). These studies, for the most part, stop at providing an outline of how these methods and techniques add value to the risk/reward sharing mechanism in IPD (Pishdad-Bozorgi and Srivastava, 2018). BIM in integration with IPD practices are also discussed in several research studies (Fischer et al., 2017, Rowlinson, 2017, Allison et al., 2018). The challenges of such integrations are explored in another stream of studies; financial challenges, difference in cost accounting between participants, and the lack of risk/reward sharing mechanism that can be accepted by all participants (Zahra Kahvandi, 2018). No workable methodology is however provided to demonstrate the interrelationship among BIM tools/dimensions and IPD stages in practical terms (Roy et al., 2018).

To this end, the paper outlines the design of an automated model of cost control system of IPD projects through integrating ABC into EVM to develop mathematical equations that support EVM to determine risk/rewards for owner and all non-owner parties. The EVM is extended by a grid to allocate the output of its CPR and SPR, subsequently, all parties can track their duties on the web system. The EVM-web system includes two kinds of reports (1) graphical report that shows the previous performance, as well as, the current state of the project. Each milestone is presented as a star inside the EVM grid, which is divided into four areas; each area represents a generic case. (2) A metrics report that shows three main values for owner and non-owner parties (reimbursed costs, profit and cost saving).

2. Information and Communication Technology (ICT) in construction management

Jacobsson and Linderoth (2010) state that the increasing of shared information in construction industry lead to the necessity of utilising Information and Communication Technology (ICT). There are several reasons beyond calling ICT applications in construction industry, namely, lack of integration between design and production (construction stage), facilitate communication among different disciplines (teams) whether internal the same organisation or cross different organisations (Söderholm, 2006).

Recently, BIM is considered as one of the application of ICT in construction industry (Latiffi et al., 2013), throughout last few years, BIM becomes mandatory in many countries, thus the rate of adopting ICT generally has been raised (Eadie et al., 2013). ICT web systems are proven their abilities to work efficiently and effectively in cost control tasks in construction industry, as web system enables all project participants to see the project status easily regardless of the participant geographical place (Ozorhon et al., 2014), for example, Li et al. (2006) and developed and tested web systems to manage and display the project performances through using EVM method. Web system is used in data management in construction throughout last decade, particularly the application of Map-based

Knowledge Management (MBKM) for contractors (Lin et al., 2006). ICT in data management facilitated the understanding trough digitalising the knowledge as a map, therefore, information is presented graphically as symbols and huge data is embedded. Therefore, the makers and users can easily communicate through specific symbols, thus redundant texts will be minimised (Wexler, 2001).The research of utilising web systems in monitoring cost/schedule projects have received significant attentions (Chou et al., 2010), particularly, utilising EVM method to display the schedule and cost simultaneously to enable stakeholders understand and track their tasks easily (Li et al., 2006).

3. Implications of cost management within BIM and IPD

In moving towards efficient project delivery, the ultimate goal is having a database of information that is available to all project participants, with confidence in its accuracy, universal utility, and clarity (Oraee et al., 2017). The main drive for adopting BIM, is managing all project documents and stages (i.e. design, planning, and costing) in a single/dynamic context, to secure the proper exploitation of available information (Abrishami et al., 2015)). BIM design elements must contain the required information in various natures, including design or management (Banihashemi et al., 2018), to acquire smartly-designed elements, rather than traditional 3D components (Pärn and Edwards, 2017). BIM users should be capable of acquiring all the required information from a single BIM elements, to make informed decisions (Elghaish et al., 2019). Four-dimensional modelling (4D BIM) can embed progress data in 3D model objects by adjusting the task-object relationship (Hamledari et al., 2017). Application of 4D BIM leads to easily operate workflows, efficient on-site management, and assessing constructability (Hartmann et al., 2008). As for the cost management, BIM is one of the most efficient Architectural, Engineering, and Construction (AEC) tools in increasing productivity on construction projects (Wang et al., 2016) . Colloquially termed as 5D BIM (Aibinu and Venkatesh, 2013), this capability of BIM offers the preferred technique for extracting quantities from 3D models, allowing cost consultants to incorporate productivity allowances and pricing values (Lee et al., 2014). The cost estimating process starts with exporting data from 3D models to BIM-based cost estimating software (e.g. CostX®) to prepare quantity take-off. Afterwards, the Bills of Quantities (BoQ) are generated and exported to an external database (Aibinu and Venkatesh, 2013). Prices and productivity allowances can also be added to project schedule preparation (Lee et al., 2014). Such automated quantification will shorten the quantity take-off processing time, and will automatically consider any changes in design – which is likely in fast-track projects (Wang et al., 2016).

Cost estimation hence has a vital role in applying IPD (AIA, 2007, Elghaish et al., 2019), and therefore, must be tracked through a scrutinising method by core team members to determine their profit, and shared benefits/risks, according to the deviation between the actual and target costs (Zhang and Li, 2014). The compensation approach structure must be capable of drawing upon effective methods, to determine cost overrun proportions, cost underrun, and any saving in total budget under the agreed cost (Elghaish et al., 2019). That is because, risk/reward proportion rely on the degree of achievement during the entire project stages (Elghaish et al., 2019). The compensation approach has two limits ; firstly, the direct, indirect, and overhead costs, which can be nominated as agreed cost, and secondly the profit-at-risk percentage after estimating the agreed cost (AIA, 2007, Zhang and Li, 2014).

The precise determination of risk perception is critical to ensure the agreed compensation structure will be implemented correctly throughout the project, so that; the risk/reward ratio can be fairly allocated among project participants. Therefore, the participant who carries more uncertain works can be compensated with higher profit-at-risk percentage (Das and Teng, 2001).

4. Earned value management

Earned value management (EVM) is a quantitative project management technique for measuring project progress, and to provide project participants with early warnings where the project is running ‘over the budget’ or ‘behind the schedule’ (PMI, 2013). Khamooshi and Abdi (2016) provided evidence of EVM being successfully applied on several real-life projects to deliver accurate cost/schedule metrics. According to Naeni et al. (2011) “earned value technique is a crucial technique in analysing and controlling the performance of a project". EVM, as recommend by PMI (2013), is an effective tool for supplying cost and schedule indicators, to measure performance through Cost Performance Ratio (CPR) and Schedule Performance Ratio (SPR) values. The granularity between project scheduling, represented through WBS, and the actual way, represented through the expenditures, is a problem in accurate implementation of EVM (Pajares and López-Paredes, 2011). The EVM system, therefore, needs to be smarter, provided with advanced capabilities, to enable a correlation between data from multiple sources, and also, automatically generating the cost control report (Lipke et al., 2009). The interoperability issue among various data sources, to build federated project cost control sheets, is best resolved through using advanced technologies and visualisation techniques (Chou et al., 2010).

5. Activity based costing

Construction projects typically rely on a fragmented structure – of participants, and this fragmentation, leads to an increase in overhead activities, and accordingly overhead costs (Mignone et al., 2016). There are several traditional cost accountant methods; Resource Based Costing (RBC) that relies on resources' cost, and Volume Based Allocation (VBA) that is based on allocating the cost of resources directly to the objects, regardless of the cost structure – direct, indirect, and overhead costs (Holland and Jr, 1999). Cost distortion, however occurs in using these traditional methods, due to conflating all indirect costs into one, which distorts the pricing of company products (Miller, 1996). Activity Based Costing (ABC) is a solution to such distortion, through allocating costs of multi-pools, and determining the overhead activities and the associated costs needed to transform the resources into activities that can deliver the final product (Kim and Ballard, 2001).

6. Research methodology

An amalgamation of *exploratory case study* and *experiment* is deemed a suitable method for accomplishing such an objective, following the arguments by Banihashemi et al. (2018). Therefore, the literature review is utilised to highlight the research gap in terms of the capabilities of proposed methods and processes —ABC, EVM and BIM—to be integrated for automated financial transactions within IPD. As such, the research commences by integrating ABC into EVM to develop mathematical formulas that can provide reliable metrics for IPD, so that the proposed formulas should shows the risk/rewards values for each party and for the entire project performance. Afterwards, a data visualisation technique based on EVM should be developed. The developed framework are validated a real-life case study since experiments are particularly effective in revealing whether the real data can support or refute any proposed procedure, as according to Zellmer-Bruhn et al. (2016)experiments can demonstrate the match, if any, between data and a proposed theory.

7. Developing the framework

The development of the framework is divided into sections, first section is to build a robust cost structure of IPD based on ABC, second section is to develop an EVM based ABC mathematical formulas to determine risk /rewards values, this therefore could enable determining the three financial transactions (Reimbursed costs, profit and cost saving properly). The third section is how BIM and web-based information system can be utilised.

7.1. Formulating IPD's cost structure based on ABC

The compensation structure in IPD relies on distinguishing direct and overhead cost such that owners and non-owner parties can manage their activities in accordance with achievements in each Limb, that's why, ABC is adopted in this research, and therefore the cost estimation should be estimated and recorded in ABC sheet as shown in figure (1). Given that BIM is highly recommended to be utilised with IPD for successful project delivery (Elghaish et al., 2019, Rowlinson, 2017), therefore, figure (1) shows how the ABC sheet can be implemented within BIM platforms (i.e. Autodesk Navisworks). In this framework, the direct and indirect costs are determined as a summation of costs of direct activities, and similarly, the overhead costs are estimated as a summation of costs of overheard activities for each trade package, all from the ABC estimation sheet. The reason behind using ABC for articulating the compensation approach is its capability to measure the degree of savings for each participant, which accordingly leads to effective and precise computation of the risk/reward sharing ratio as shown in figure (2). Furthermore, the cost saving share for owner differs from the non-owner participants given the difference between the cost overhead saving in the organisation sustaining level and project level. Thus, the goal of determining the participants sharing risk/reward ratio using this approach is to ensure equitable and a more applicable approach.

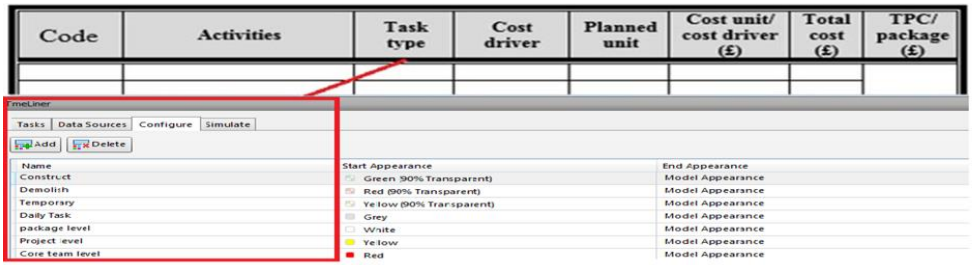


Figure 1. ABC structure sheet with correlation between 4D/5D BIM

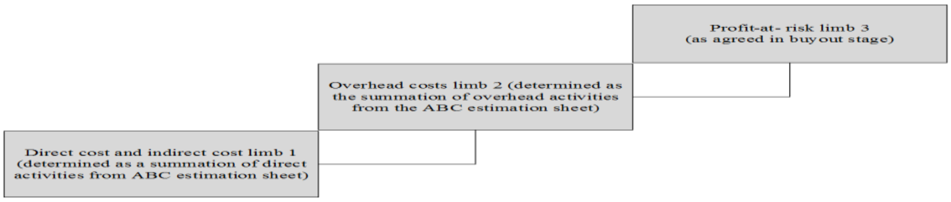


Figure 2..Compensation under the IPD approach using ABC estimation

7.2. Developing EVM based ABC extensions

Below table (1) illustrates the developed mathematical formulas based on EVM and ABC in order to determine the risk/rewards values for owner and non-owner parties. It can be seen that there are models in corresponding to each case, hence this will enable automating the payment process (recording the risk/rewards values automatically, and this could speed the rate of adopting IPD for successful project delivery.

Table 1. Proposed EVM-based ABC extensions

Case	EVO	Developed models	Terminologies
On cost/schedule	EVO =1	$\text{Rewards value} = \left((\text{EVO}) \times \text{P@R Per}\right) \times \text{MVoLIMB2} \quad (1)$ $\text{MV for R or RD for each party} = \text{Rewards value} \times \text{PoO or PoNO} \quad (2)$	MVoLIMB2 represents the monetary value of LIMB2 (£); MV for R/RD for each party represents the monetary value for Risk or Rewards for each participant (£); and PoO/PoNO represents the proportion of owner or non-owner party (%)
Ahead of schedule and/or cost underrun	EVO >1	$\text{CSoOC for NO} = \sum \text{CSoOOA from ABC sheet} + \sum \text{CSoOPA from ABC sheet} + \text{NOARP} \quad (3)$	CSoOC for NO represents the overhead cost saving for non-owner participants (£); CSoOOA from ABC estimation sheet represents the overhead organisation activities costs' saving from the ABC estimation sheet (£); CSoOPA from ABC estimation sheet represents the overhead

		$\text{CSoOC for O} = \sum \text{CSoOPA from ABC sheet} \times \text{OARP} \quad (4)$	project activities costs' saving from the ABC estimation sheet (£); NOARP represents the Non-Owner Agreed Rewards Proportion (%); CSoOC for O represents the overhead cost saving of for owner participants (£); and OARP represents the owner agreed rewards proportion (%).
Behind schedule and/or cost overrun	EVO <1	$\text{DC} = \sum \text{DAC from ABC estimation sheets} \quad (5)$ $\text{Rewards value} = \big((\text{OoEVMG} - 1) + \text{P@R Per}) \times \text{MVoP@Rper}\big) \quad (6)$	DC represents the direct cost (£); DAC from ABC estimation sheets represents the direct activities' costs from the ABC sheet as BCWS (£); RV represents the Rewards Value (£); MVoP@Rper represents the monetary value of Profit@Risk percentage (£).

An EVM grid is developed to display the outcome of EVM's CPR and SPR, the EVM-grid divides the project into four areas (see figure 3), where each area represents the project situation and is distinguished by a specific colour. Through allocating potential project cases on the grid, whilst considering X-axis as the schedule and the Y-axis as the cost, each area is then divided into small squares around the planned point. The user should determine the value of the CPR and SPR and enter them into the grid as positive or negative percentage to determine the project situation at each milestone or for each package. Furthermore, the quantity surveyor should mark the square in accordance with CPR and SPR percentages, to determine the cumulative progress throughout the project execution stages. Thereafter, the 'Profit-at-Risk' percentage will be shared in accordance with the output of the developed EVM-Based IPD grid.

7.3. The integration of EVM-Grid web system and BIM

The flow of data in the proposed model will be from the documentation and the buyout stage to the close out stage, with highlighting BIM integration at each stage, as described below.

During the documentation stage, core team members conduct cost estimation based on ABC and loading the costs to the corresponding activity – whether the activity is direct, indirect, or overhead. This can be implemented through estimating costs using a 5D BIM platform (i.e. Navisworks) after configuring its layers in accordance with ABC levels. Subsequently, BCWS values can be prepared through exporting data that are created through 4D/5D BIM platform to another software package like Microsoft Project. Hence, the buyout stage takes place to agree on the percentage of profit-at-risk (P@R %), as well as, risk/reward among owner/non-owner parties. Subsequently, the agreed upon P@R% is added to BCWS to develop project compensation approach, and all project data (BCWS for each package, P@R percentage, risk/reward sharing %) are recorded to enable determining the actual percentages within the construction stage. Once the construction stage begins, the project manager should start loading the project information (CPR and SPR) to the EVM-Web grid, as shown in Figure 9.

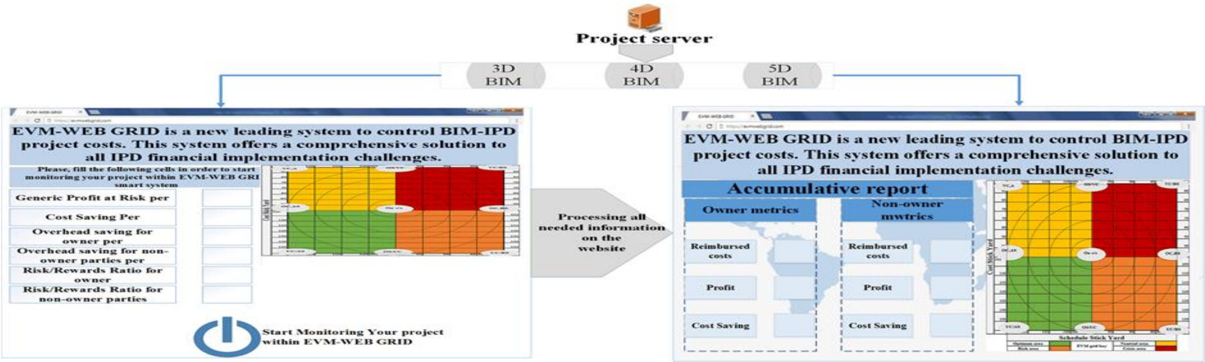


Figure 3. EVM-web system interoperability

8. Validation and result analysis

To validate the proposed methodology, the model was applied to a case study; a property development company, whose managers decided to build a new house. The costs of implementing IPD can be determined from the conceptualisation stage to buyout stages. The compensation structure was agreed upon as follows; (1) the agreed profit-at-risk percentage was 20%, (2) the saving cost allocation percentage for overhead project level cost was 70% for non-owner participants and 30% for owner, (3) the non-owner risk/reward ratio was 80% and 20% for owner party. Although, within the existing IPD model, the owner does not get any proportion from P@R%, it is assumed that the owner gets a proportion from P@R% for two reasons: providing any service such as participating in managing project workflow, and showing capabilities of the presented framework to work on various scenarios. (4) the direct and indirect cost limit (Limb 1) was £118,484.9; (5) Limb 2, which involved direct, indirect, overhead costs was £190,484.9; and (6) Limb 3, which comprises from the total cost and the profit-at-risk percentage, which was £228,581.9.

8.1. Determining the risk/rewards values

Figure ٤ summarises the above-mentioned scenario steps and results of implementing the framework for both owner and non-owner parties. The benefit of implementing EVM framework is allocating the risk/reward among the core team members within the IPD approach, as discussed earlier. The scenarios displayed two scenarios for an EVM output less and greater than 1. The sharing proportion was calculated accordingly, based on the developed framework.

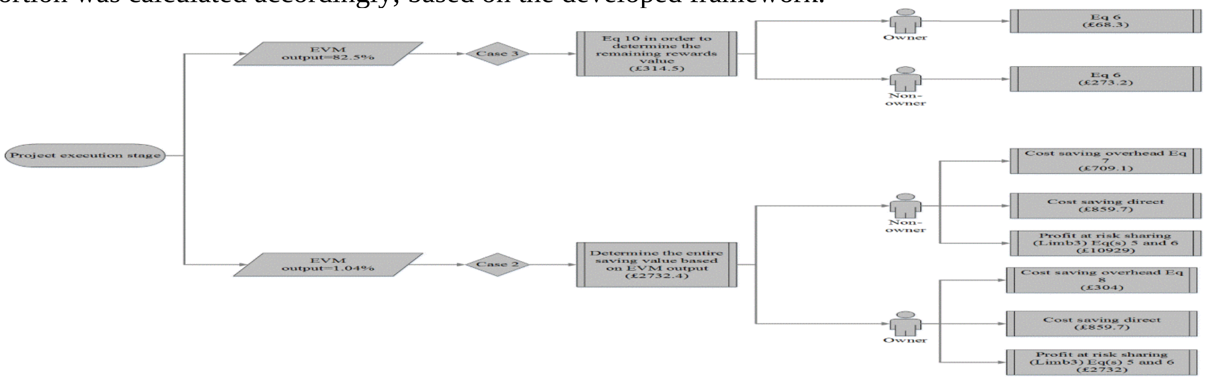


Figure 4. Results analysis flowchart

8.2. The applicability and integration of BIM and EVM-web system

In order to show how BIM and EVM-web can be utilised, the presented data in scenario (2) are shown in below figure 5. Figure 5 shows the BIM dimensions (3d, 4/d and 5D) that have been developed for this case study and all project data will be retrieved from these three models as the case study supports the integration of IPD and BIM. According to reviewing 4D BIM as clear in figure (11), some works have been completed and milestone 1 is by the end of week 1 in March, subsequently, the project parties should be able to follow the overall performance whether graphically or by metrics report.

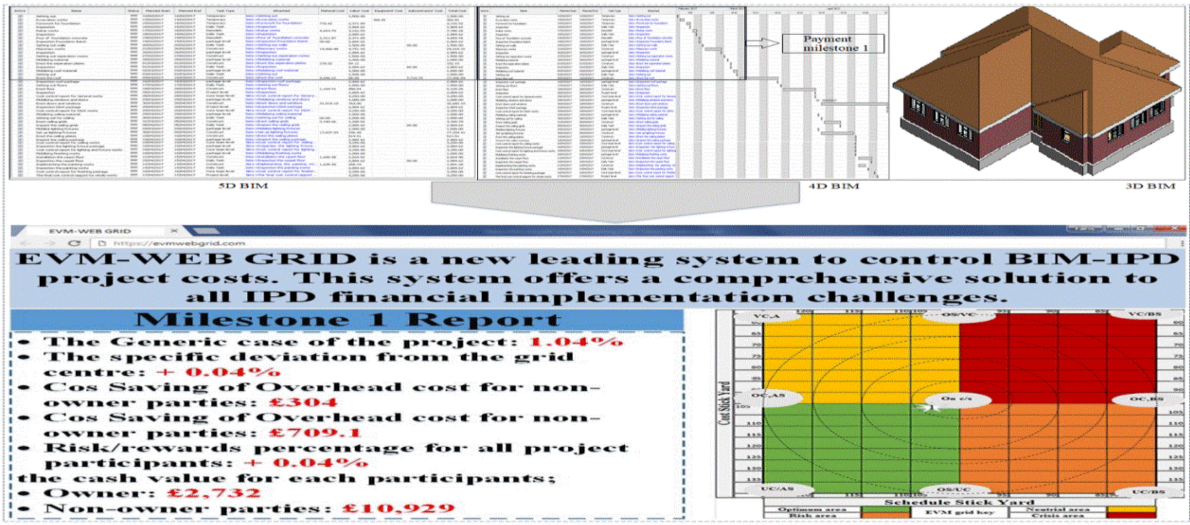


Figure 5. Result analysis of displaying risk/rewards values on EVM-web system

9. Conclusion and future directions

This research proposed a comprehensive approach to manage the financial tasks within the IPD approach, the entire IPD's cost management process is visited to identify the weak/capable points, and afterwards set of methods such as ABC, EVM and BIM are integrated into a single / dynamic process.

This study is novel in several ways. That is, the paper introduces an innovative grid that locates the Cost Performance Ratio (CPR), and Schedule Performance Ratio (SPR) to provide a picture of project position in terms of cost and schedule. Furthermore, it integrates the EVM-Grid with the ABC estimating method to optimise the cost structure, which is positively reflected in the compensation structure. In addition, the findings present models that deal with risk/reward sharing, through considering new directions, to ensure fair sharing using ABC sheets and distinguish between the direct and overhead cost saving. For the overhead cost, the framework distinguishes between the sustaining/organisation level and the project level. Additionally, the EVM-Grid has been developed as a web system to allow the participants to easily track their project.

In practical terms, the findings will be invaluable for novice BIM users, given the simplicity and user-friendliness of the proposed models. All the tasks are aligned with the implementation stages and easily expressed to allow novice users to collect the required data promptly. The interventions and outcome of this research will be used to develop an automated payment platform based on Hyperledger fabric (blockchain).

References

ABRISHAMI, S., GOULDING, J., POUR RAHIMIAN, F. & GANAH, A. 2015. Virtual generative BIM workspace for maximising AEC conceptual design innovation: A paradigm of future opportunities. Construction Innovation, 15, 24-41.

AHMAD, I., AZHAR, N. & CHOWDHURY, A. 2019. Enhancement of IPD Characteristics as Impelled by Information and Communication Technology. Journal of Management in Engineering, 35, 04018055.

AIA. 2007. Integrated Project Delivery: A Guide [Online]. The American Institute of Architects. Available: https://www.aia.org/resources/64146-integrated-project-delivery-a-guide [Accessed 26 June 2018].

AIBINU, A. & VENKATESH, S. 2013. Status of BIM adoption and the BIM experience of cost consultants in Australia. Journal of Professional Issues in Engineering Education and Practice, 140, 04013021.

ALLISON, M., ASHCRAFT, H., CHENG, R., KLAWENS, S. & PEASE, J. 2018. Integrated Project Delivery: An Action Guide for Leaders.

BANIHASHEMI, S., TABADKANI, A. & HOSSEINI, M. R. 2018. Integration of parametric design into modular coordination: A construction waste reduction workflow. Automation in Construction, 88, 1-12.

CHEUNG, S. O., SUEN, H. C. & CHEUNG, K. K. 2004. PPMS: a web-based construction project performance monitoring system. Automation in construction, 13, 361-376.

CHOU, J.-S., CHEN, H.-M., HOU, C.-C. & LIN, C.-W. 2010. Visualized EVM system for assessing project performance. Automation in Construction, 19, 596-607.

DAS, T. & TENG, B.-S. 2001. A risk perception model of alliance structuring. Journal of International Management, 7, 1-29.

EADIE, R., BROWNE, M., ODEYINKA, H., MCKEOWN, C. & MCNIFF, S. 2013. BIM implementation throughout the UK construction project lifecycle: An analysis. Automation in construction, 36, 145-151.

ELGHAISH, F., ABRISHAMI, S., ABU SAMRA, S., GATERELL, M., HOSSEINI, M. R. & WISE, R. 2019. Cash flow system development framework within integrated project delivery (IPD) using BIM tools. International Journal of Construction Management, 1-16.

FISCHER, M. J. A., KHANZODE, A., REED, D. P. & ASHCRAFT, H. W., JR. 2017. Integrating project delivery, Hoboken, New Jersey, John Wiley & Sons Inc.

HAMLEDARI, H., MCCABE, B., DAVARI, S. & SHAHI, A. 2017. Automated schedule and progress updating of IFC-based 4D BIMs. Journal of Computing in Civil Engineering, 31, 04017012.

HARTMANN, T., GAO, J. & FISCHER, M. 2008. Areas of Application for 3D and 4D Models on Construction Projects. Journal of Construction Engineering and Management, 134, 776-785.

HOLLAND, N. L. & JR, D. H. 1999. Indirect Cost Categorization and Allocation by Construction Contractors. Journal of Architectural Engineering, 5, 49-56.

HOSSEINI, M. R., MAGHREBI, M., AKBARNEZHAD, A., MARTEK, I. & ARASHPOUR, M. 2018. Analysis of Citation Networks in Building Information Modeling Research. Journal of Construction Engineering and Management, 144, 04018064.

JACOBSSON, M. & LINDEROTH, H. C. 2010. The influence of contextual elements, actors' frames of reference, and technology on the adoption and use of ICT in construction projects: a Swedish case study. Construction management and Economics, 28, 13-23.

KHAMOOSHI, H. & ABDI, A. 2016. Project duration forecasting using earned duration management with exponential smoothing techniques. Journal of Management in Engineering, 33, 04016032.

KIM, Y.-W. & BALLARD, G. Year. Activity-based costing and its application to lean construction. In: Proceedings of the 9th Annual Conference of the International Group for Lean Construction, Singapore, August, 2001 2001 National University of Singapore.

LATIFFI, A. A., MOHD, S., KASIM, N. & FATHI, M. S. 2013. Building information modeling (BIM) application in Malaysian construction industry. International Journal of Construction Engineering and Management, 2, 1-6.

LEE, S.-K., KIM, K.-R. & YU, J.-H. 2014. BIM and ontology-based approach for building cost estimation. Automation in Construction, 41, 96-105.

LI, J., MOSELHI, O. & ALKASS, S. 2006. Internet-based database management system for project control. Engineering, Construction and Architectural Management, 13, 242-253.

LIN, Y.-C., WANG, L.-C. & TSERNG, H. P. 2006. Enhancing knowledge exchange through web map-based knowledge management system in construction: Lessons learned in Taiwan. Automation in Construction, 15, 693-705.

LINTHICUM, D. S. 2003. Next generation application integration: from simple information to Web services, Addison-Wesley Longman Publishing Co., Inc.

LIPKE, W., ZWIKAEL, O., HENDERSON, K. & ANBARI, F. 2009. Prediction of project outcome: The application of statistical methods to earned value management and earned schedule performance indexes. International Journal of Project Management, 27, 400-407.

MA, Z., ZHANG, D. & LI, J. 2018. A dedicated collaboration platform for Integrated Project Delivery. Automation in Construction, 86, 199-209.

MIGNONE, G., HOSSEINI, M. R., CHILESHE, N. & ARASHPOUR, M. 2016. Enhancing collaboration in BIM-based construction networks through organisational discontinuity theory: a case study of the new Royal Adelaide Hospital. Architectural Engineering and Design Management, 12, 333-352.

MILLER, J. A. 1996. Implementing activity-based management in daily operations, The University of Michigan, John Wiley & Sons.

NAENI, L. M., SHADROKH, S. & SALEHIPOUR, A. 2011. A fuzzy approach for the earned value management. International Journal of Project Management, 29, 764-772.

ORAEE, M., HOSSEINI, M. R., PAPADONIKOLAKI, E., PALLIYAGURU, R. & ARASHPOUR, M. 2017. Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review. International Journal of Project Management, 35, 1288-1301.

OZORHON, B., KARATAS, C. G. & DEMIRKESEN, S. 2014. A web-based database system for managing construction project knowledge. Procedia-Social and Behavioral Sciences, 119, 377-386.

PAJARES, J. & LÓPEZ-PAREDES, A. 2011. An extension of the EVM analysis for project monitoring: The Cost Control Index and the Schedule Control Index. International Journal of Project Management, 29, 615-621.

PÄRN, E. A. & EDWARDS, D. J. 2017. Conceptualising the FinDD API plug-in: A study of BIM-FM integration. Automation in Construction, 80, 11-21.

PISHDAD-BOZORGI, P. & SRIVASTAVA, D. 2018. Assessment of Integrated Project Delivery (IPD) Risk and Reward Sharing Strategies from the Standpoint of Collaboration: A Game Theory Approach. Construction Research Congress 2018. New Orleans, Louisiana: American Society of Civil Engineers.

PMI 2013. A guide to the project management body of knowledge (PMBOK® guide), Newtown Square, Pennsylvania, Project Management Institute.

ROWLINSON, S. 2017. Building information modelling, integrated project delivery and all that. Construction Innovation, 17, 45-49.

ROY, D., MALSANE, S. & SAMANTA, P. K. 2018. Identification of Critical Challenges for Adoption of Integrated Project Delivery. Lean Construction Journal.

SÖDERHOLM, A. 2006. Kampen om kommunikationen. Kampen om kommunikationen-Om projektledningens Informationsteknologi. Sweden: Research report, Royal Institute of Technology.

WANG, K.-C., WANG, W.-C., WANG, H.-H., HSU, P.-Y., WU, W.-H. & KUNG, C.-J. 2016. Applying building information modeling to integrate schedule and cost for establishing construction progress curves. Automation in Construction, 72, 397-410.

WEXLER, M. N. 2001. The who, what and why of knowledge mapping. Journal of knowledge management, 5, 249-264.

ZAHRA KAHVANDI, E. S., AHAD ZARE RAVASAN, AND TAHA MANSOURI 2018. An FCM-Based Dynamic Modelling of Integrated Project Delivery Implementation Challenges in Construction Projects. Lean construction journal, 63-87.

ZELLMER-BRUHN, M., CALIGIURI, P. & THOMAS, D. C. 2016. From the Editors: Experimental designs in international business research. Journal of International Business Studies, 47, 399-407.

ZHANG, L., CAO, T. & WANG, Y. 2018. The mediation role of leadership styles in integrated project collaboration: An emotional intelligence perspective. International Journal of Project Management, 36, 317-330.

ZHANG, L. & LI, F. 2014. Risk/reward compensation model for integrated project delivery. Engineering Economics, 25, 558-567.

Decentralized Autonomous Organizations and Network Design in AEC: a conceptual framework

Marijana Sreckovic[1,*] and Josef Windsperger[2]
[1]Institute for Interdisciplinary Building Process Management, TU Wien, Austria
[2]Department of Business Decisions and Analytics, University of Vienna, Austria
[*]email: marijana.sreckovic@tuwien.ac.at

Abstract

Digital technologies are revolutionizing collaboration and value co-creation across traditional industry boundaries and thus generating the need for adaptive and innovative business models, new and flexible network forms as well as new digital processes and capabilities. Digital technologies are also changing the innovation logic of an organization. In recent years, digital tools and platforms have emerged as facilitators of innovation and collaboration, enabling loosely coupled networks of firms to merge knowledge and capabilities for the creation of competitive advantage. Exploring interdependencies between organizational structures, technology architecture and the coupling between system components, which would enable better collaborative processes, is currently one of the emerging research questions in the digital economy. In that context, the implementation of blockchain technology calls for a transformation of business models, roles, processes and workflows. It requires a new kind of governance and organization, which diverges from the common management processes present today. To address this gap this paper proposes an integrative conceptual framework for a blockchain-based organization and the resulting decentralized autonomous organizations (DAOs). Due to the complexity of value chains in the Architecture, Engineering and Construction (AEC) industry and the traditionally slow implementation of innovation, the primary aim of our research is to show blockchain-applicability in a general organizational context in this first step. Hence, enabling a better understanding for practitioners and researchers how building blocks of common organizational design need to be re-conceptualized for the implementation of blockchain technologies in AEC, as use cases, practical demonstrations and standards are still missing.

Keywords: DAO, Blockchain, Knowledge Assets, Decision Rights, Value Chain

1. Introduction

In the last decades Information and Communication Technology has been widely used as a facilitator of AEC collaboration, with the application of building information modelling (BIM). Nevertheless, successful implementation of evolving digital technologies, such as BIM or distributed ledger technologies (DLT), and furthermore the generation of innovation processes in the digital economy, require changes in traditional organizational processes, a dynamic strategic fit and the development of adequate organizational capabilities for the implementation of technological advancements.

The rapid development of the digital economy and different technologies has also led to radical changes in traditional business processes and value chains, opening new paradigms for organisational design, where organisations are moving from hierarchical to user-centric resp. actor-oriented and network-centric forms (Koch and Windsperger, 2017). Blockchain and smart contracts, and furthermore the resulting development of novel innovative forms of organizing, such as decentralized autonomous organizations (DAOs), are inevitably changing industries and potentially finding their way into AEC, which is traditionally slower in the implementation of digital innovation than other industries. Thererfor the question arises how to adapt technology advancements stemming originally from the cryptocurrency industry such as blockchain and smart contracts for AEC and furthermore how to implement DAOs in the AEC value chain. In that context use cases, practical demonstrations and standards are still missing but necessary for the testing of adequate applicability of the aforementioned technologies (Adams et al.,2017, Turk and Klinc, 2017).

To address this gap this paper proposes an integrative conceptual framework for a blockchain-based organization and the resulting DAO. Due to the complexity of value chains in the AEC industry and the slow implementation of innovation, the primary aim of our research is to show blockchain-applicability in a general organizational context in this first step. Hence, enabling a better understanding for practitioners and researchers how building blocks of common organizational design need to be re-conceptualized for the implementation of blockchain technologies. Therfore, based on our 3 propositions from chapter 2 we conceptualize the integrative framework for the explanation of DAOs, by answering the following 3 questions: What are the knowledge characteristics of the value chain activities? How are the knowledge characteristics changing due to digitalization resp. digital technologies? How are residual decision rights changing due to digital technologies such as blockchain? As DAOs in AEC are still in their infancy, with only potential use case applications found in literature (Li et al, 2019) the main goal of this research is therefor showing the transformational implications for organizational design in the blockchain economy, and presenting a pathway for future research in the implementation of new technologies.

This paper is organized as follows: In chapter 2 we introduce our conceptual framework, in chapter 3 our model, followed in chapter 4 by the discussion and conclusion.

2. Conceptual framework

The implementation of blockchain technology calls for a transformation of business models, roles, processes (Adams et al., 2017; Li et al., 2019) and workflows. It requires a new kind of governance and organization, which diverges from the common management processes present today. Future research should investigate how decision rights are allocated in the blockchain economy and their degree of centralization/decentralization (Beck et al., 2018). Following this suggestion, we argue that in addition to the allocation of decision rights, characteristics of knowledge assets and the value chain need to be examined for blockchain-based organisation and the resulting DAOs. Therefor, in our interdisciplinary conceptual framework we identify the need to integrate knowledge characteristics (degree of intangibility of knowledge assets), digital technologies (blockchain and smart contracts) and the allocation of decision rights (property rights approach) with the value chain for the explanation of decentralized autonomous organizations. (Fig. 1).

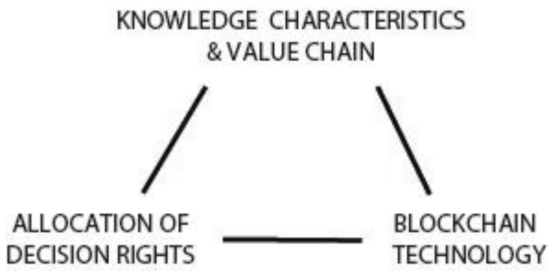


Figure 1: Integrative framework for a DAO

2.1 Knowledge characteristics and the value chain

Hedlund (1994: 75) differentiates between *tacit* or nonverbalizable, intuitive, unarticulated knowledge, and explicit, *articulated* knowledge, which can be expressed verbally or in writing, computer programs, drawings. He identifies four different carriers or agents of knowledge: the *individual*, the *small group*, the *organization*, and the *interorganizational* (network) domain. The knowledge characteristics relevant for allocation of decision rights are the degree of intangibility of knowledge assets. These tacit or intangible knowledge assets (Hall, 1993; Klein & Leffler, 1981) refer to the knowledge and skills (know-how) that cannot be easily codified and transferred to other agents. Tacit know-how is hence characterized by a low degree of contractibility. The transfer of intangible knowledge requires personal and face-to-face contact (Teece, 1981; von Hippel, 1994). In AEC intangible know-how includes emotional, cultural or aesthetical requirements for design, whereas *articulated* knowledge includes explicit know-how, such as time, costs, quantity requirements and discipline-specific skills, all of which can be expressed verbally or in writing, computer programs, drawings.

Intangible and tangible knowledge assets are present at every level of the organization resp. in the value chain (Fig. 2). The performance of activities in the value chain leads to the accumulation of firm's intangible assets, knowledge, routines and skills, which under the circumstances of a relatively stable environment should accumulate over time.

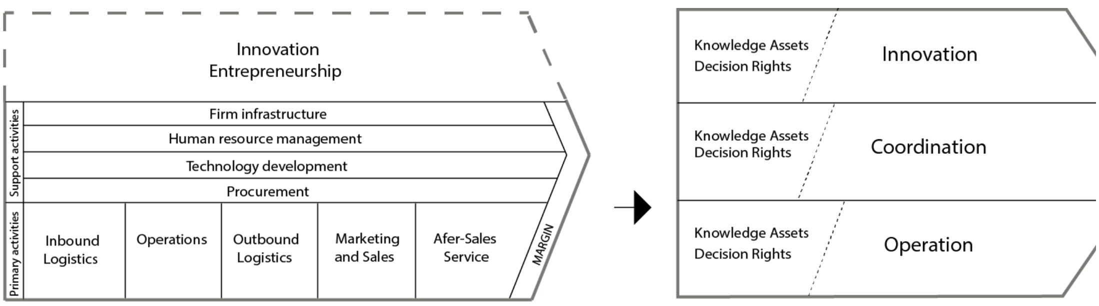


Figure 2: An extended value chain model (adapted from Srećković, 2018)

The value creation processes are specific for each industry or organizational typology and they hold the key sources for competitive advantage. Porter's value chain framework (Fig. 2) disaggregates the firm into a sequential chain of value activities, distinguishing between primary activities as those responsible for producing, marketing, and delivering the product, and support activities defined as those "that create or source inputs or factors (including planning and management) required to do so" (Porter 1991: 102). Several scholars (Armistead and Clark 1993; Stabell and Fjeldstad 1998; Løwendahl 2005; Zott and Amit 2013) argue that Porter's value chain framework, while it is well suited to analyze and describe the main value creation process of a generic manufacturing company, is inadequate for many service organizations or professional service firms (i.e., medicine, engineering, architecture, law), as well as new networked organizational forms, which cannot relate to the descriptive terms of the primary activities (inbound logistics, operations, outbound logistics, marketing, and sales) and their sequential character. In reconfiguring his value chain for the operational flow for the delivery of a service, Porter (1998) focuses primarily on cost advantages that can be achieved through more efficient or differentiated primary activities in the new and improved value chain. Nonetheless, in this reconfigured value creation process, the support activities of a firm's infrastructure, technology, human resource management, and procurement are not explored or amended. Sreckovic (2018) closes this gap by introducing an extended value chain concept of Porter (1985), with the addition of a third dynamic level (innovation and entrepreneurship) to his original model (Fig. 2). The extended value chain is comprised of activities in operation (operational level), coordination (organizational level) and innovation (strategic level). Knowledge and resources from the operational, organizational, and strategic level of the firm are bundled and uniquely combined through time and experience to form capabilities and intangible knowledge assets that generate and sustain competitive advantage. In this constant process, the organization is adapting to the changing market environment, demands, and processes, through innovation and entrepreneurship.

Proposition 1: Intangible and tangible knowledge assets are present at every level of the organization resp. in the value chain. Depending on the complexity of the value chain processes and the number of stakeholders involved, the distribution of intangible and tangible knowledge assets is dispersed in activities of operation, coordination and innovation, and managed accordingly.

2.2 Decision rights and the concept of centralization/ decentralisation

The concept of decision rights refers to the authority to deploy and use the firm's assets (Grossman & Hart, 1986; Hansmann, 1996; Simon, 1951). There are theoretical and empirical studies dealing with the allocation of decision rights in organizational economics. But due the novelty of applying innovations stemming from the cryptocurrency industry to traditional organizations forms, conceptual models and research is lacking in how the new organizational paradigm of DAO, based on a blockchain, will change industries, such as AEC.

According to the property rights theory decision rights are either **nonresidual** (**specific**) or **residual**. Nonresidual decision rights are explicitly specified in contracts (Demsetz, 1988), and refer to the use of contractible (articulated, explicit) knowledge, which can be easily codified and transferred. For instance, ''specific user rights over a computer may be rights to use it to run a particular program in a particular manner in a particular time period for some specific purpose'' (Foss and Foss, 1998, p: 9). Residual decision rights refer to the authority to influence the use of intangible (tacit) knowledge, not easily codified and articulated in contracts. This tacit, system-specific knowledge as ''sticky'' information (von Hippel, 1994) cannot be easily communicated and stipulated in contracts due to high transaction cost.

Organizational efficiency requires that those with the responsibility for decisions also have the knowledge valuable to those decisions (Jensen and Meckling, 1992). Colocation of decision rights with knowledge can be achieved by transferring the knowledge to the person who has the decision right or by transferring the decision rights to the person with the knowledge. Such transfers mean that knowledge transfer costs determine the **degree of decentralization or centralization** of decision making. Decision rights tend to remain in the CEO's office when the costs of transferring knowledge to the central office is low, and decision rights tend to be delegated to lower levels of the hierarchy when the firm primarily produces knowledge that is costly to transfer to the CEO (Malone, 1997).

Proposition 2: The allocation of residual decision rights depends on the characteristics of knowledge assets: The more important a person´s intangible knowledge asset for the generation of the residual income relative to another person, the more residual decision rights should be assigned to that person or network.

2.3 Blockchain, Smart Contracts and DAO

Based on Blockchain and Smart Contracts, Distributed Autonomous Organizations (DAOs) are created. Blockchain is a decentralized, transaction-based directory based on a network in which transactions are no longer handled by a central office, an intermediary (e.g., bank), but directly from computer to computer. The transaction data are thus stored locally (Buchleitner and Rabl, 2017). Blockchain offers further advantages over traditional centralized systems (Scherk and Pöchhacker-Tröscher, 2017):

- Transaction data is encrypted (access control) stored on all the computers (single source of truth) of the network members, enabling synchronization of databases;
- Data cannot be manipulated (immutability of record); It ensures that all participants in the system have identical information. Blockchain thus creates a historical source for all data in the system, which means that there is no need for trust between the participants or central authorities (disintermediation of trust), since manipulation of the data is almost impossible; Consensus models ensure that only correct data can be included in the blockchain and not manipulated (data integrity); Participants in the network must agree on what information is included in the system. It must be understood that the first transaction that is recorded is the only valid one and cannot be subsequently changed or removed from the system;
- identical copy is stored on all computers (no potential single point of failure);
- processes in the network run according to a specified program code (process integrity);
- self-executing smart contracts can be used to program complex, conditional transactions and actions (programmability);

Smart contract "is a digital protocol that automatically executes given technological processes within a transaction without an intermediary" (Buchleitner and Rabl, 2017). This digital protocol defines which conditions lead to which decisions and thus creates an automated processing of contracts that are implemented automatically (in codes) by monitoring these conditions in real time and enforcing contract components (Scherk and Pöchhacker-Tröscher, 2017). The advantages that result are: safety, verifiability, transparency and immutability.

Possible applications for Blockchain and Smart Contracts in the built environment include: (Kinnaird et al., 2017, Coyne and Onabolu, 2018, Shen and Pena-Mora, 2018, Munsing et al, 2017): sharing economy, e-government, digital building submission, power industry, microgrids, ownership, and transfer of real etate rights (Real Estate Implementations), Intellectual Property Rights, Supply Chain (Circular Economy in the Life Cycle of a Building), Smart City Applications. With the help of smart contracts, it should also be possible in the future to design and sign contracts, define and evaluate necessary data for real estate valuation, to commission service providers along the value chain, to map real estate data and to store sensitive data (PwC, 2017). The benefits of using smart contracts in AEC are: accuracy, transparency, risk management, compliance, cost efficiency.

DAOs are decentralized organizations with standardized, automated processes that can replace and handle complicated coordination processes (which can be represented as routines) in the value chain through software rules (protocols) (Hsieh and Vergne, 2018). They thus exist as computer code in the cloud and have no management or hierarchy. Changes in the automated, standardized organizational processes happen through a democratic process of the partners of the DAO. For the use of decentralized organizational systems in the AEC it is necessary to find standardized or novel forms of cooperation between project members and teams in segments of the value chain that can be expressed using algorithms. To this end, it is essential to also identify and better understand the role of intermediaries, and what added value they generate at what cost to the project (Belle, 2017) - thereby reducing transaction costs (coordination, information costs), risks minimized and time saved. These forms of organization have not yet been explored in the lifecycle of buildings.

Proposition 3: Blockhain will facilitate a shift toward decentralization when tacit knowledge which was previously exclusive to higher levels of the organization can be codified (in smart contracts) and implemented in a automatized process; blockhain will facilitate a shift toward centralization when the transfer of tacit knowledge moves from lower to higher levels in the organization.

3. The model of DAO

In our integral conceptual framework, we argue that for the explanation of blockchain-organizing and the resulting DAOs, it is necessary to look at the value chain transformation through technology and its effect on decentralisation of activities of operation, coordination and innovation (Fig. 3). Centralisation of decision making is only efficient if the central planner has the knowledge that is specific in time and place (von Hayek, 1935, 1940). Due to the CEO’s limited information-processing capabilities organizations must delegate decision making power (see also Van Zandt, 1999; Van Alstyne, 1997). The question is what means delegation in the context of an organizational form which is managed through rules coded in smart contracts resp. how does the value chain, decision rights and knowledge assets change with blockchain (Fig 4)?

In Fig 3, scenario 1 depicts the value chain of a network organization (which is common in the AEC industry), where knowledge assets and decision rights are available on the innovation, coordination and operational level of the firm. Accordingly in Fig 4, scenario 1, shows decision rights and knowledge assets for a network contract, with a relatively low degree of contractibility, resulting in a relatively low ratio between specific decision rights and residual decision rights. This means that there is a relatively low degree of tangible, codifiable know-how in the network organization which can be specified in contracts; and a higher degree of intangible knowledge assets at different levels of the organization. To summarize, contractual completeness is defined by the ratio between specific and residual decision rights. The lower the contractibility of knowledge (e. g. due to high intangibility of knowledge assets and uncertainty), the lower is the probability to formulate specific rights and the more residual decision rights are assigned to another partner in a network, or within the organization to another person resp. level of the value chain, and the lower is the degree of contractual completeness.

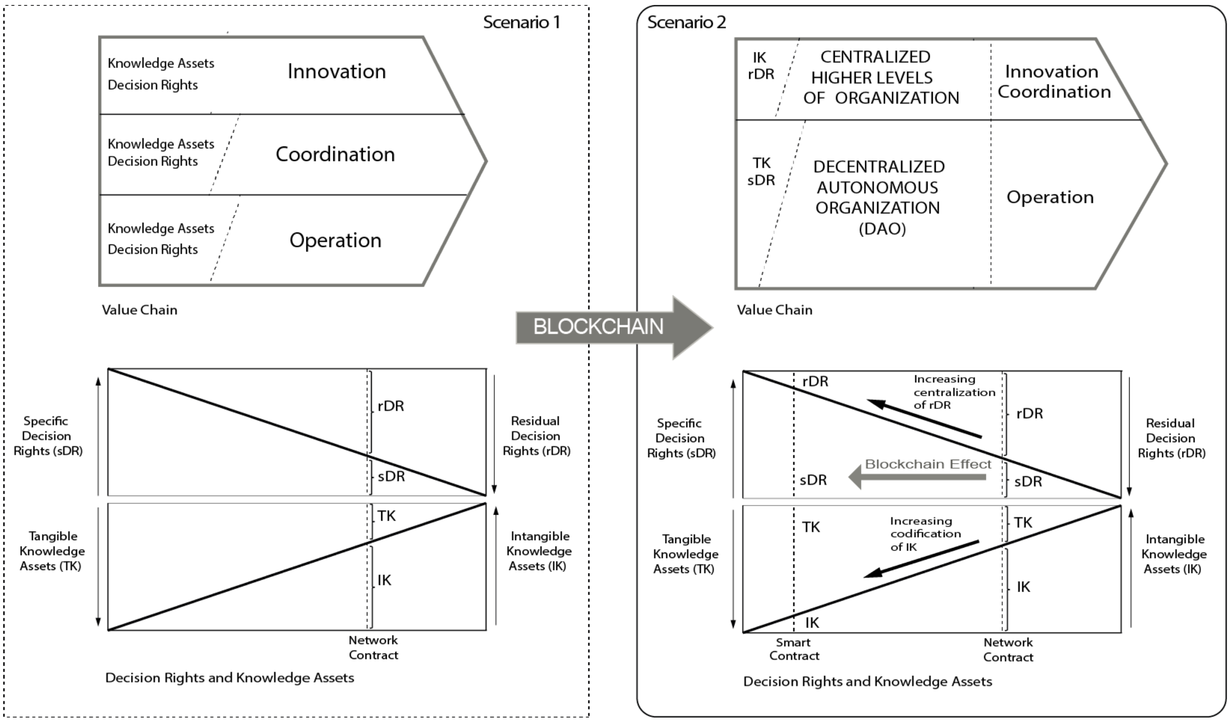


Figure 3: Value chain, Knowledge Assets, Decision Rights transformation through blockchain

The most general feature of blockchain technology is decentralization. Decentralization is closely connected to centralization. DAOs are organizations managed through rules and regulation, specified in smart contracts, running on a blockchain platform. Their resources are organized according to rules agreed in advance. They are actually a system of self-organization. Scenario 2 in Fig. 3 and 4, shows the transformation of the value chain through blockchain technology, where the DAO has the ability to replace centralized intermidieries for operation and coordination activities, under the premise that knowledge assets are codifiable and can be automated. This means that the value chain takes another form, where automated operational processes are organized in a DAO, whereas residual decision rights in coordination and innovation (with intangible knowledge asset) are increasingly centralised, either on the highest level of the value chain in the organisation or the network. This means that the implementation of blockchain makes new forms of governance necessary which are still to be explored, especially concerning the their applicability for AEC.

4. Discussion and Conclusion

Blockchain technology calls for a rethinking of the existing workflows, and this technology has even the potential to help exploit the potential of BIM workflows. Blockchain supported workflows would increase the transparency, speed up the planning processes and simplify the communication by providing real-time insight into the planning stage, and facilitate the enquiry possibilities for each planning step.

But new technological advances such as blockchain and smart contracts are still underutilized for the AEC industry, or not yet scientifically researched in the BIM-based planning and construction process. Complex, time-consuming processes and data management tasks continue to be done by planners, which could be automated. Opportunities to make workflows in building planning more transparent, comprehensible, consistent, efficient, cost-effective and time-saving remain unused. This would also provide the possibility of real-time communication in the model. In an industry where collaboration is based on expertise and a high level of trust, the potential of new decentralized organizational systems (DAOs) should be explored, enabling innovative forms of collaboration between project members and teams in segments of the value chain. These could be expressed in an automated way (based on smart contracts), in particular if it would save the time and costs of administration, reporting, control, accountability and risk transfer. For this purpose, it is also necessary to examine the role of intermediaries and to better understand them, or what added value they generate at what cost for the project or planning process.

With this paper we are contributing to the knowledge in organisational economics, with the aim to first provide a general insight into new forms of organizing with blockchain technology. And in a further step to explore the applicability of blockchain in a use case setting, which is still in development. Furthermore, the goal is to support future research activities into the application of DAOs in the AEC with our integral conceptual framework.

References

Adams, R., Parry, G., Godsiff, P., & Ward, P. (2017). The future of money and further applications of the blockchain. Strategic Change, 26(5), 417-422. doi:10.1002/jsc.2141.

Aghion, P., & Tirole, J. (1997). Formal and real authority in organization. Journal of Political Economy, 105, 1-29.

Armistead, S. G., & Clark, G. (1993). Resource activity mapping: The value chain in service operations strategy. The Service Industries Journal, 13(4), 221. doi:10.1080/02642069300000070.

Barzel, Y. (1997). Economic analysis of property rights. New York. Cambridge: Cambridge University Press.

Beck, R., Müller-Bloch, C., & King, J. L. (2018). Governance in the blockchain economy: A framework and research agenda. Journal of the Association for Information Systems, 19(10), 1020-1034. doi:10.17705/1jais.00518.

Brickley, J.A., Smith, C.W., & Zimmerman, J.L. (1995). The economics of organizational architecture. Journal of Applied Corporate Finance, 8(2), 19-31.

Buchleitner, C., & Rabl, T. (2017). Blockchain und Smart Contracts – Vom Ende der Institutionen. ECOLEX – Fachzeitschrift für Wirtschaftsrecht, 4-14.

Coyne, R., & Onabolu, T. (2018). Blockchain for architects: Challenges from the sharing economy. Architectural Research Quarterly, 21(4), 369-374. doi:10.1017/S1359135518000167.

Davidson, S., De Filippi, P., & Potts J. (2016). Economics of Blockchain. Available at SSRN: https://ssrn.com/abstract=2744751 or http://dx.doi.org/10.2139/ssrn.2744751.

Demsetz, H. (1988). The Theory of the Firm Revisited. Journal of Law, Economics and Organizations, 4, 141-162.

Grossman, S., & Hart, O. (1986). The costs and benefits of ownership: a theory of vertical and lateral integration. Journal of Political Economy, 94, 691-719.

Hall, R. (1993). A framework linking intangible resources and capabilities to sustainable competitive advantage. Strategic Management Journal,14, 607-618.

Hansmann, H. (1996). The ownership of enterprise. Cambridge: The Belknap Press.

Hart, O., & Moore, J. (1990). Property rights and the nature of the firm. Journal of Political Economy, 98, 1119-1158.

Hedlund, G. (1994). A model of knowledge management and the N-form corporation. Strategic management journal, 15(S2), 73-90.

Hsieh, Y.-Y., & Vergne, J.-P. (2018). Bitcoin and the rise of decentralized autonomous organization. Journal of Organization Design, 7(14). doi:10.1186/s41469-018-0038-1.

Hugoson, M.Å. (2009). Centralized versus Decentralized Information Systems. In: Impagliazzo, J., Järvi, T., Paju, P. (eds), History of Nordic Computing 2. HiNC 2007. IFIP Advances in Information and Communication Technology, 303. Springer, Berlin, Heidelberg.

Jensen, M.C., & Meckling, W.H. (1992). Specific and general knowledge and organizational structure. In: Werin, L., Wijkander, H. (eds), Contract economics. Oxford: Basil Blackwell, 251-274.

Kinnaird, C., Geipel, M., & Bew. M. (2017). Blockchain Technology - How the Inventions Behind Bitcoin are Enabling a Network of Trust for the Built Environment. ARUP.

Klein, B., & Leffler, K.B. (1981). The role of market forces in assuring contractual performance. Journal of Political Economy, 89, 615-641.

Koch, T., & Windsperger, J. (2017). Seeing through the network: Competitive advantage in the digital economy. Journal of Organization Design, 6(6). doi:10.1186/s41469-017-0016-z.

Li, J., Greenwood, D., & Kassem, M. (2019). Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. Automation in Construction, 102, 288-307. doi:10.1016/j.autcon.2019.02.005.

Løwendahl, B. R. (2005). *Professional service firms*. Copenhagen: CBS Press.

Malone, T.W. (1997). Is empowerment just a fad? Control, decision making and IT. Sloan Management Review, 38(2), 23-35.

Munsing, E., Mather, J., & Scott, M. (2017). Blockchains for Decentralized Optimization of Energy Resources in Microgrid Networks, UC Berkeley, Working Papers, 8.

Norta, A. (2015). Creation of smart-contracting collaborations for decentralized autonomous organizations. Paper presented at the International Conference on Business Informatics Research.

Penzes, B., Kirkup, A., Gage, C., Dravai, T., & Colmer, M. (2018). Blockchaihn Technology in the Construction Industry - Digital Transformation for High Productivity (Online). Available at: https://www.ice.org.uk/ICEDevelopmentWebPortal/media/Documents/News/Blog/Blockchain-technology-in-Construction-2018-12-17.pdf (Accessed 18.4.2019)

Porter, M.E. (1991). Towards a dynamic theory of strategy. Strategic Management Journal, 12, 95-117. doi:10.1002 /smj.4250121008.

Porter, M.E. (1998). Competing across locations: enhancing competitive advantage through a global strategy. Harvard Business School Press.

Rajan, R.G., & Zingales, L. (2000). The governance of the new enterprise. In: Vives, X. (ed), Corporate governance: theoretical and empirical perspectives, Cambridge.

Scherk, J., & Pöchhacker-Tröscher, G. (2017). Die Blockchain – Technologiefeld und wirtschaftliche Anwendungsbereiche. BMVIT - Bundesministerium für Verkehr, Innovation und Technologie.

Shen, C., & Pena-Mora, F. (2018). Blockchain for Cities - A Systematic Literature Review. IEEE, 6, 76787-76819. doi:10.1109/ACCESS.2018.2880744.

Simon, H.A. (1955). A Behavioral Model of Rational Choice. Quarterly Journal of Economics, 69, 99-118.

Sreckovic, M. (2018). The performance effect of network and managerial capabilities of entrepreneurial firms. Small Business Economics, 50, 807-824. doi:10.1007/s11187-017-9896-0.

Stabell, C. B., & Fjeldstad, Ø. D. (1998). Configuring value for competitive advantage: on chains, shops, and networks. Strategic Management Journal, 19(5), 413–437. doi:10.1002/(SICI)1097-0266(199805)19:5.

Turk, Z., & Klinc, R. (2017). Potentials of Blockchain Technology for Construction Management. Creative Construction Conference 2017 (CCC 2017), 19-22 June 2017, Primosten, Croatia, Procedia Engineering, 196, 638-645.

Van Alstyne, M. (1997). The state of network organization: a survey in three frameworks. Journal of Organizational Computing and Electronic Commerce, 7, 83-152. doi:10.1080/10919392.1997.9681069.

Van Zandt, T. (1999). Decentralized information processing in the theory of organizations. In: Sertel, M. (ed), Contemporary economic issues. London, 125-160. doi: 10.1007/978-1-349-14540-9_7.

von Hayek, F.A. (1935). The nature and history of the problem. In: Hayek, F.A. (ed), Collectivist economic planning, London.

von Hayek, F.A. (1940). Socialist calculation: the competitive 'solution'. Economica, 7, 125-149.

Von Hippel, E. (1994). Sticky information and the locus of problem solving: implications for innovation. Management Science, 40, 429-439.

Wruck, K.H., & Jensen, M.C. (1994). Science, specific knowledge, and total quality management. Journal of Accounting and Economics, 18, 247-287.

Zott, C., & Amit, R. H. (2013). Crafting business architecture: the antecedents of business model design. Academy of Management Proceedings, 1. doi:10.5465/AMBPP.2013.15289abstract.

Automated building energy modeling for existing buildings using computer vision

Ipek Gursel Dino[1 2, *], Esat Kalfaoglu[1], Alp Eren Sarı[1], Sahin Akin[1], Orcun Koral Iseri[1],

A. Aydın Alatan[1], Sinan Kalkan[1], Bilge Erdogan[2]

[1] Center for Image Analysis (OGAM), Middle East Technical University, Turkey

[2] Department of Architecture, Middle East Technical University, Turkey

[2] Heriot-Watt University, United Kingdom

*email: ipekg@metu.edu.tr

Abstract

Improving the energy efficiency of existing buildings requires energy models that accurately represent the building and quantify various performance measures. Manual energy modeling has been proven to be inefficient, labor-intensive and error-prone. Therefore, the automation of energy modelling is critical. Existing approaches for 3D geometry extraction using 3D laser scanning are promising, but their high cost and high level of operational expertise prevent their widespread use. Computer vision methods, particularly 3D reconstruction can effectively support the creation of 3D building models. An additional component of energy models is the building envelope's thermal characteristics. IR thermography can be used to determine the thermal transmittance of the external walls with data collection in both visible and thermal bands. This paper presents a method for the semi-automated energy modeling of existing buildings. A conventional structure-from-motion (SfM) pipeline is utilized, which consists of several algorithms that compute a 3D point cloud from the images of the room to be modelled. The system matches the image points of the same scene points on different views by using Scale Invariant Feature Transform (SIFT) features and L2 Cascade Hashing with precomputed hashed regions methods to match the calculated features and perform 3D reconstruction using incremental SfM. Following, the two cameras are calibrated, after which each point in the point cloud is matched with the corresponding temperature measured by a thermal camera after using the intrinsic and extrinsic parameters of the optical and thermographic cameras. A planar surface representing each surface is calculated, and the elimination of objects other that building surfaces is performed by a Random Sample Consensus (RANSAC) algorithm. Finally, thermal transmittance values of the outer walls are calculated using the measured surface temperatures. The results are validated in two steps. The first step calculates the difference between the geometry of the 3D ground truth model of the actual room and the generated 3d model. The second step is a comparative analysis between the calculated energy use of two energy models (using Energyplus) constructed with different methods: the manual method (using as-built drawings and theoretical thermal transmittance values) and the proposed method. The difference between the simulation results of these two models are finally comparatively analyzed. The initial results are expected to be indicative of the benefits of using semi-automated methods of energy model construction for existing buildings.

Keywords: 3D reconstruction, thermography, building energy modeling, building energy performance

1. Introduction

Improving the energy efficiency of existing buildings call for approaches that precisely quantify energy use through energy modeling and simulation, as a response to the increasing complexity of buildings and systems. Energy simulation has the potential to reduce buildings' environmental impact, improve occupant comfort and indoor environmental quality and facilitate innovation in AEC (Hensen & Lamberts, 2011). For existing buildings, energy simulations have the potential to complement real monitored building data for operational optimization or retrofit. While a building can only react to actual contextual conditions such as local weather, occupancy, operational patterns, a simulation-based virtual model can move back in time to analyze the building's past behavior to calibrate the program for improved predictive potency, or move forward in time to predict the building's response to alternative control scenarios (Mahdavi, 2001). Dynamic energy simulation tools adopt a forward-modeling approach that begins with a description of the building and components, providing a physical description of the building (design geometry, construction data, thermal zones, internal heat gain, infiltration and usage profiles), its systems (system types and sizes, control schedules, outdoor air requirements) and components (HVAC components) (Wang, Yan, & Xiao, 2012). Amongst these, the former is the most fundamental category that the other categories are based upon. Therefore, a correct description of the building is critical for the reliability of simulation-based performance assessment.

Despite the key role of simulations in performance assessment, the difficulties in the construction of energy models has been a major obstacle against their widespread use. Manual modelling efforts are based on building documentation (i.e. drawings, specifications, schedules) and walk-through audits. However, this process is labor-intensive and might result in disparities between the building and the model. This is due to (1) buildings undergoing undocumented major changes, (2) the degradation of materials over time, and (3) the difficulties in capturing internal load patterns and dynamic components for extended periods of time. ICT techniques can help automate energy modelling. 3D laser scanning is a promising technology for 3D geometry extraction for planning retrofit, spatial planning, resource and construction progress tracking (Akinci et al., 2006; Bosché & Guenet, 2014a, 2014b; Bosché, Guillemet, Turkan, Haas, & Haas, 2013; Dimitrov & Golparvar-Fard, 2014; Mahdjoubi, Moobela, & Laing, 2013; Valero, Adan, & Cerrada, 2012). However, its high cost, high level of operational expertise and complexity prevent its widespread use.

An effective and inexpensive alternative is 3D reconstruction. Computer vision research has been studying 3D reconstruction in any scale by utilizing the multiple photos taken by any camera at any time. Any 3D structure generation pipeline has a number of stages including calibration, pose estimation, triangulation and parameter optimization of the 3D structure (Sweeney, 2015). While 3D reconstruction from a collection of images has been previously addressed widely, many research problems remain unsolved in each stage of a generic pipeline from an energy modeling viewpoint. The latter method, thermal imaging, is the act of recording temperature variations of a surface in visible images. Thermal imaging offers a non-destructive and rapid way to calculate material thermal properties (U-value) from surface temperatures. When 2D images and thermal images are captured and merged, a 3D building model with material properties can be generated. A novel approach needs to be developed for the registration of thermal (low spatial resolution) images captured by thermographic cameras on the initial 3D models. Moreover, the approach should address several requirements regarding energy modeling. The first requirements is the generation of the 3D model of the building or the room. Energy models represent building surfaces as planar surfaces without thickness (thickness is typically added elsewhere by material association) to calculate heat transfer. For each room, a seamless volume bounded by a minimum number of surfaces is needed to be defined to avoid unnecessary computational cost. Therefore, the 3D point cloud captured through 3D reconstruction needs to be processed to generate a polygon model. Moreover, during 3D reconstruction, a complete optical view of surfaces that allows the construction of a complete wall surface might not be available due to occlusion or clutter. The second requirement is the calculation of thermal resistance data of external wall surfaces. Material thermal properties is a determinant factor in building energy use. Thermal imaging can help calculate thermal resistance values of building constructions from surface temperatures. An existing method that calculates R-values at the level of 3D points is used in this research. Final, data integration with energy modeling tools is needed to transfer the captured data an energy modeling tool, EnergyPlus.

2. Material and methods

This paper proposes a method for the semi-automated energy modeling of existing buildings using 3D reconstruction. Specifically, a pipeline that merges digital 2D optical images and thermal images of a room into a single 3D building model with surface thermal resistance values is developed. The pipeline uses visual band images registered with corresponding thermal images as input data. The main steps of the pipeline are the calibration of the imaging system, 3D model generation, fusion and thermal resistance calculation (Figure 1). Details for each step is provided in the following subsections. We used two types of images together, which are visual band and thermal images. Visual band images are utilized for 3D model generation and thermal images are utilized for thermal resistance calculation.

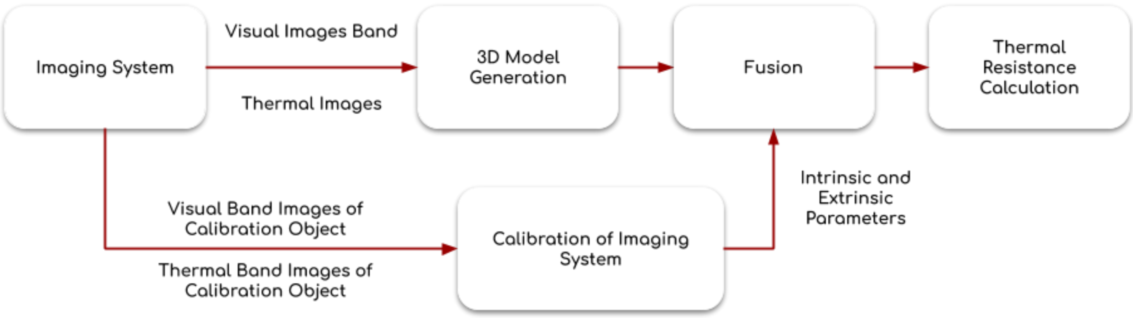


Figure 1. The proposed pipeline

2.1 The Calibration of the Imaging System

Physical properties of a camera are defined by its intrinsic parameters, that are focal lengths and optical centers. Therefore, it is essential to first calculate the intrinsic parameters of the visual band and thermal cameras while generating a 3D model. The process of computing the intrinsic and extrinsic (rotation and translation) parameters of a camera at the same time is known as camera calibration in computer vision. We calibrated both our visual band and thermal cameras using MATLAB's camera calibration toolbox. We also calculate the relative pose (i.e. rotation matrix and translation vector) between coordinate systems of the visual band and thermal cameras to map pixels between these cameras.

a. Visual Band Calibration: We manufactured a checkerboard calibration object using a piece of cardboard, whose images were taken by the visual band camera (Figure 2 - Left). We calculated the intrinsic and extrinsic parameters of the visual band camera with 20 pictures of the calibration object captured by the camera.

b. Thermal Calibration: The same calibration is used for the calibration of the thermal camera since the checkerboard pattern is observable in the thermal image, (Figure 2 - Right). We similarly calculate the intrinsic and extrinsic parameters of the thermal camera using 20 images of the calibration object captured by the thermal camera.

c. Pose estimation between the two cameras: The intrinsic parameters (translation and rotation) were obtained with respect to the same calibration object for both visual band and thermal cameras. We exploit this fact to calculate the relative translation and rotation between the two cameras. It should be noted that since both cameras capture images of the calibration object at the same time, the calculation of translation and rotation between the two cameras was possible due to the fact that two sensors are mounted on the same body. We calculate the rotation matrices and translation vectors between each image in the visual band and thermal cameras, and finally take the average of the estimated data to find a single robust rotation matrix and translation vector.

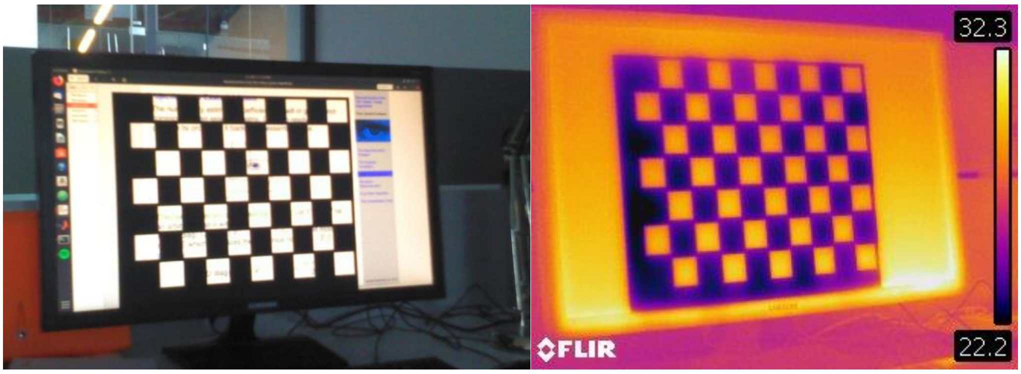


Figure 2. The checkerboards used for calibration

2.2 3D Model Generation

For generating an accurate 3D model of the room, we mainly rely on a widely-used technique in computer vision, namely, Structure from Motion (SfM). In SfM, a set of images of an environment are used to obtain 3D information about the environment. These images are assumed to be captured at different positions (and possibly with different cameras) and to contain overlapping views of the environment. From the overlapping views, or more technically, the visual information that correspond to the same 3D entities in the environment, the positions of the cameras and the 3D coordinates of the pixels can be identified. For 3D model generation, we adapted OpenMVG's tools to form a pipeline, which is composed of visual information (feature) description, visual feature matching, SfM, multiview stereo and enhancement through interaction (Moulon, Monasse, Perrot, & Marlet, 2017).

a. Visual Feature Description: Not every pixel in an image carries visually meaningful information. To find those useful pixels (also called keypoints) as well as representing information at and around those keypoints, we use the Scale-Invariant Feature Transform (SIFT) method (Lowe, 2004). SIFT finds keypoints by looking at intensity changes in an image at multiple scales. If there is a consistent change at a pixel at different scales, then that pixel is assumed to carry useful information. For representing such a keypoint, SIFT calculates a summary of how the intensity changes around the keypoint in the form of a 128-dimensional vector.
b. Visual Feature Matching: The computed feature vectors are first matched using the algorithm, which results in a set of potential matches between features in different views (Cheng, Leng, Wu, Cui, & Lu, 2014). Following, a geometric filtering operation is employed to choose the geometrically meaningful matches using AC-RANSAC (A Contrario RANdom SAmple Consensus) (Moulon et al., 2012).
c. Structure from Motion (SfM): For SfM, we use the method proposed by Moulon et al. (2012) due to its robustness and adaptive capacity. The method constructs an initial 3D model using the best matching two images and continues reconstruction by adding the remaining images repeatedly.

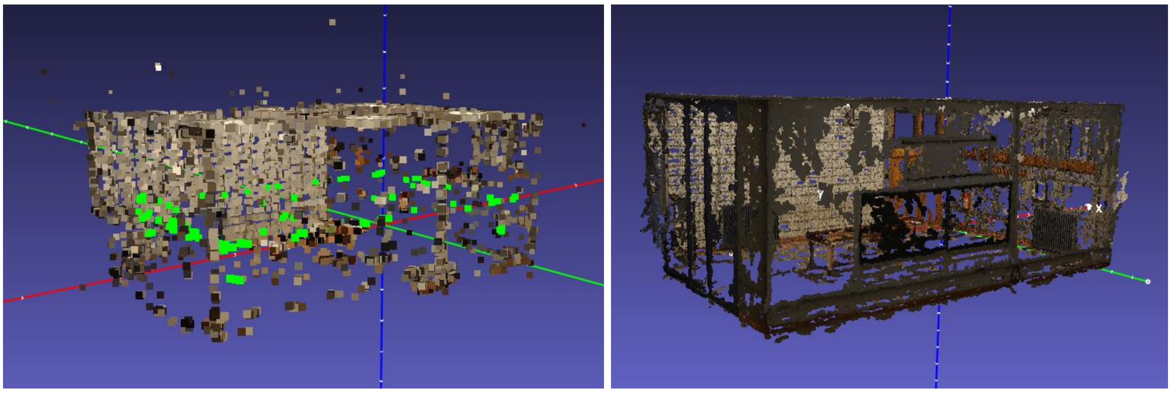


Figure 3. The sparse 3D model (left) and the densified 3D point cloud

d. Densification using Multi-view Stereo (MVS): Since a dense 3D point cloud is needed for 3D reconstruction, it is essential to densify the sparse 3D point cloud computed by SfM. For densification, we employed an algorithm for Multiview stereopsis developed by Furukawa et al. (2010), which densifies a given 3D point cloud by interpolation. The sparse and dense point clouds can be seen in Figure 3.
e. Enhancement through Interaction: In the previous step, a 3D model of the environment has been obtained. To finalize the model for the following steps, several post-processing phases were followed:

i. Adjusting the Scale and Pose of the 3D Model: We first select some points from the captured visual band images (Figure 4) and find their actual 3D coordinates by measuring the physical distances between them. Following, we compute a similarity transformation with non-linear optimization that provides the lowest mean squares error. This similarity transformation is applied onto the reconstructed 3D point cloud to correct the scale, orientation and translation of the 3D point cloud. However, this process can introduce some degree of imprecision, since might not be possible to match the exact pixel/location in the calculated 3D points.

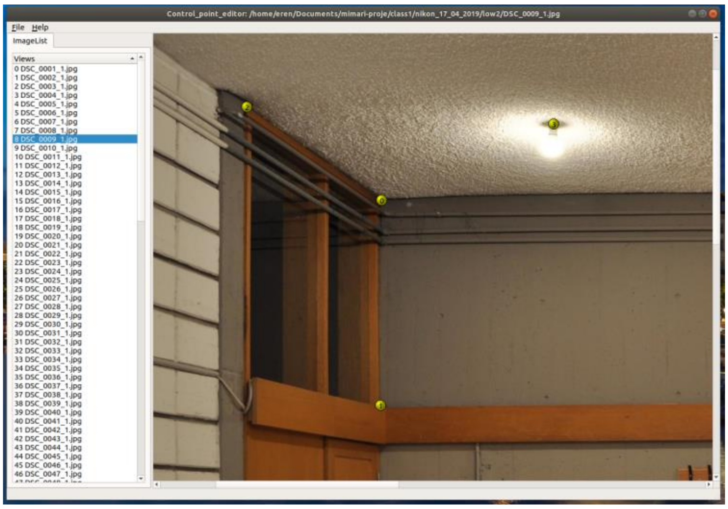


Figure 4: Point selection from captured images

ii. *Calculating the surfaces in the model:* The equations of a plane for each surface (walls, floor and ceiling) are computed for the points that lie within a rectangular shape that is manually marked by the user on the images (Figure 5). Plane estimation from a set of 3D points is performed using least-squares estimation. Specifically, the Singular Value Decomposition method is used, where the last column of the V matrix represents the plane equation. After plane fitting, the corners of the room are calculated by intersecting the corresponding three planes for each corner (Eq 1),

$$\boldsymbol{X}_{Nx4} = \boldsymbol{U}_{NxN}\boldsymbol{\Sigma}_{Nx4}\boldsymbol{V}_{4x4}^{T}, \qquad \text{Eq. 1}$$

where $\boldsymbol{X}$ is a Nx4 matrix whose first 3 rows contain the 3D points in the selected rectangle and the fourth row contains a vector of 1's with dimensions Nx1, the matrices $\boldsymbol{U}, \boldsymbol{\Sigma}, \boldsymbol{V}$ are the singular value decomposition (SVD) of the $\boldsymbol{X}$ matrix. The last column of $\boldsymbol{V}$ is the plane coefficient, which provides the best fit to the selected 3D points.

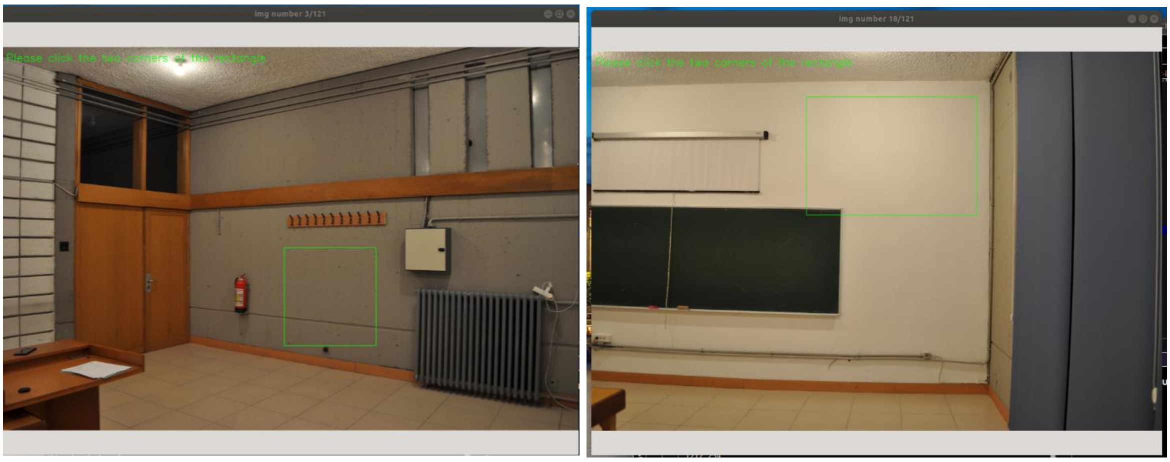


Figure 5. Point selection from the east (left) and south (right) walls

iii. *Window and Door Detection:* The corners of the windows and the doors are selected by the users. An example of selecting the window corners can be seen in Figure 6-C. After this step, the corresponding 3D points for each corner point are calculated by projecting the 3D point cloud onto the corresponding image and searching for the best match for the points selected and they are projected onto the previously calculated planes.

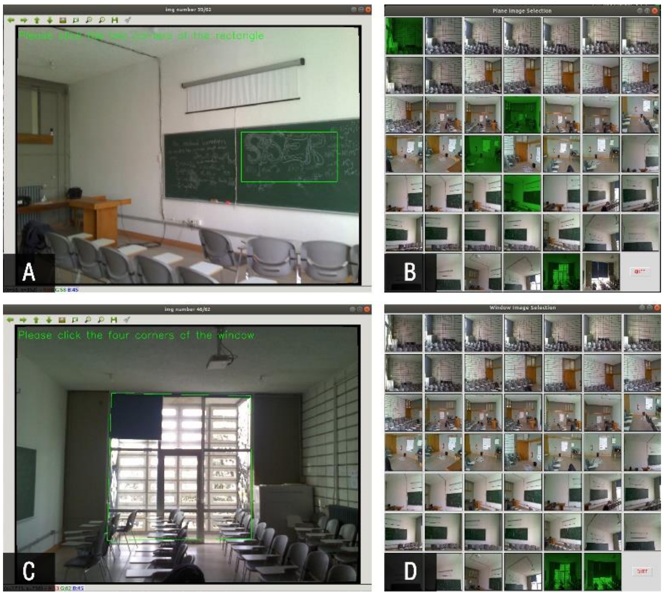


Figure 6. A. Identification of the wall planes by selecting certain areas on the surfaces, B. Selection of the surface photos for surface creation, C. Identification of the window surfaces by selecting a certain area on the desired window. D. Selection of the desired window photos for window creation

2.3. Fusion with Thermal Data

During this step, the captured thermal images are mapped to the 3D model to calculate the thermal resistance values for the external walls. To this end, the (intrinsic) parameters of visual band (RGB) and thermal cameras and the relative 3D rotation and 3D translation between them are used. The following steps were followed.

- Calculating the rotation and translation of each visual band image by multiplying each RGB camera's projection with the inverse of the visual band camera's intrinsic matrix.

$$P_{RGB} = K_{RGB}[R_{RGB}t_{RGB}]$$
$$[R_{RGB}t_{RGB}] = K^{-1}P_{RGB} \quad \text{Eq. 2}$$

where P_{RGB} is the projection matrix of the RGB camera, K_{RGB} is the intrinsic matrix of the RGB camera, R_{RGB} is the rotation matrix of the RGB camera and t_{RGB} is the translation vector of the RGB camera.

- Multiplying the rotation matrices calculated at the previous step with the rotation matrix that corresponds to the rotation between RGB and thermal cameras, and adding the translation vector between RGB and thermal cameras to each RGB camera's translation. The rotation and the translation values of each thermal camera are calculated as follows:

$$R_{thermal} = R_{relative}R_{RGB}^{T} \quad \text{Eq. 3}$$
$$t_{thermal} = R_{RGB}^{T}t_{RGB} + t_{relative}$$
$$P_{thermal} = K_{thermal}[R_{thermal}t_{thermal}]$$

where Rthermal is the rotation matrix of the thermal camera, Rrelative is the rotation matrix of the rotation difference between the RGB and the thermal cameras, tthermal is the translation vector of the thermal camera, trelative is the translation vector of the translation difference between the RGB and the thermal camera, Pthermal is the projection matrix and Kthermal is the intrinsic matrix of the thermal camera.

- Stacking the calculated rotation matrices and translation vectors into matrices, and multiplying these matrices with the intrinsic matrix of the thermal camera.
- Each 3D point of the point cloud is projected onto thermal images' planes using the previously calculated projection matrices. Afterwards, the depth and the projected coordinates are checked. If the depth and the projected coordinates are both positive and within the image's coordinates, they are accepted as point correspondences and the RGB color of the thermal image point is assigned to its corresponding 3D point (Figure 7).

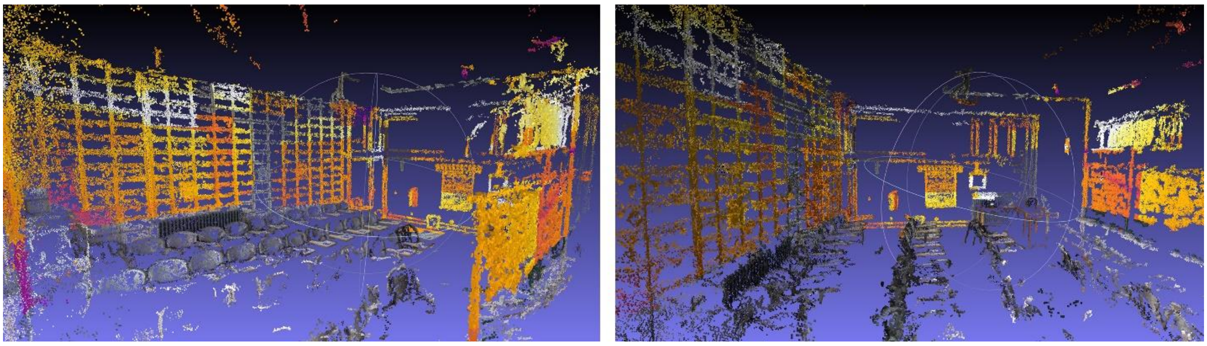


Figure 7. Juxtaposition of the thermal images on the point cloud.

2.4. Calculation of Thermal Resistance

Thermal resistance values of the external walls are calculated using the method proposed by Ham et. al (Ham & Golparvar-Fard, 2013). For each wall, the mean surface temperature is first calculated using the thermal point cloud and calculated planes and these mean temperature values are used to calculate the thermal resistance values. The equation for thermal resistance calculation is given by Ham et al. as:

$$R = \frac{|T_{inside,air} - T_{outside,air}|}{\alpha_{con} \times |T_{inside,air} - T_{inside,wall}| + \epsilon \times \sigma \times |T_{inside,wall}^{4} - T_{inside,reflected}^{4}|}, \quad \text{Eq. 4}$$

where α_{con} is the convective heat transfer coefficient, ε is the thermal emissivity, and σ is the Stefan-Boltzmann coefficient. Following this equation, room mean air temperature is measured using a thermometer and the reflected temperature is measured by capturing an image of a crumpled aluminum coil with the thermal camera and taking the mean value of the temperatures of the aluminum coil.

Together with the described pipeline, a graphical user interface (GUI) was designed to allow the users select the optical and thermographic images for 3D reconstruction, manually mark the surfaces of walls on optical images for plane construction and mark the boundaries of windows and doors to define these elements in the model. Once the previous steps are completed, the generated data (corner points of planes, R values, window and door points) is written in XML format with an XML schema developed by us. This file is read by a parser to construct a surface model for 3D model validation (section 3.1), and by OpenStudio SDK, an open-source framework that provides access to EnergyPlus object attributes (Weaver et al., 2019) for building energy modeling (section 3.2).

3. Results

The developed method was implemented in a classroom with an area of 46.48 m^2 in an educational building. Both electrooptic images and thermal images are captured using a FLIR E60 camera. FLIR 60 has a thermal sensitivity of <0.05°C, with an 800-pixel resolution for infrared images (320 x 240) and 3.1-megapixel resolution digital camera. The images were captured, and measurements were taken on 24 December 2018 at 6:00AM, to achieve a quasi-steady-state condition of heat transfer. The captured images, both electrooptic and thermal, were processed through the proposed pipeline. During this process, only the walls, ceiling and floor are used for model construction. The results of two comparative analyses are presented in the following sections.

3.1 3D model validation

This section presents the results of the comparative analysis between the 3D surface model generated using the above-mentioned pipeline and a 3D ground truth model that was previously obtained through 3D laser scanning. Laser scanning was carried out using a high-precision laser scanner (Faro Focus 120), after which a surface model was manually generated. This allowed us to benchmark between the two models using several metrics including (a) the Euclidean distances between surface vertices, (b) the absolute difference between surface vertex coordinates, (c) the differences between six surface normals, and (d) the difference between room volumes (Figure 8). To calculate the first three metrics, we first align the two models by intersecting one vertex of each model (Vertex 5).

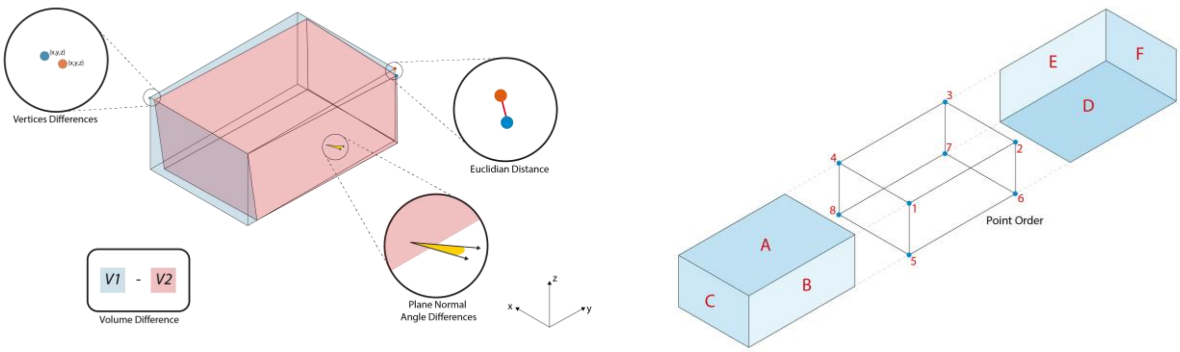


Figure 8. Comparison metrics, where the blue box represents the ground truth geometry and the red represents the generated geometry (left) and the principles of model alignment (right).

The results can be seen in Table 1. The difference between plane normals are calculated as 0.87, 1.06, 0.29, 0.56, 0.36 and 0.42 respectively for surfaces A to F. The precision of the results is within tolerable limits for energy modeling. Finally, the volumes of the two models are calculated as 170.78

and 156.14 m^3 for the ground truth and calculated geometries, which amount to a -8.5% difference. This error mostly stems from the scaling and pose adjustment steps. Since the points are selected by mouse clicks, selecting the exact points that correspond to the calculated 3D point correspondences remain a serious challenge against model precision. A feasible way of decreasing the error is the use of higher resolution images as input, which can enable more precise point selection.

Table 1. Euclidean and absolute differences between surface vertex coordinates of the two models

Vertex Id	Difference in x-dimension (m)	Difference in y-dimension (m)	Difference in z-dimension (m)	Euclidian Distance (m)
1	-0.02	-0.06	0.11	0.13
2	-0.33	-0.08	0.02	0.34
3	-0.30	-0.21	-0.04	0.37
4	-0.01	-0.23	0.06	0.24
5	0.00	0.00	0.00	0.00
6	-0.31	-0.02	-0.03	0.32
7	-0.28	-0.19	-0.08	0.35
8	0.01	-0.21	-0.05	0.22

3.2 Building energy modeling

In this section, we benchmark the energy simulation results of the energy model built using the proposed approach and using theoretical R-values. First, an EnergyPlus model of the classroom was built with OepnStudio, using the previously generated building surfaces. Following, two alternatives are considered for the R-values of the external wall. The first is the calculated value using the pipeline, and the second is the theoretical R-value associated with reinforced concrete material of the same thickness as the actual wall in the DesignBuilder material library. The other material thermal characteristics used in both models can be found in Table 2. The windows are modeled as double-glazed window (U= 2.6 W/m2-k, SHGC = 0.75, VT = 0.8). The internal load templates defined in DesignBuilder for people, lighting and equipment are used. The heating setpoint and setback temperatures are set to 22 C° (5:00AM-6:00PM during weekdays) and 18 C° respectively. Infiltration is set to 25ACH at 50Pa. The simulation run period was set to 24-30 December, which was the week that the actual measurements were taken. The variables in Equation 4 were measured as $T_{inside,air}$ = 23.1 C°, $T_{outside,air}$ = 1.0 C° and $T_{inside,reflected}$ = 27.0 C°. The U value was calculated as 2.0 W/m2-k, which is %40 lower that the theoretical value. However, it is consistent with a previous study that presents in-situ measurements of the same building wall using Infrared Thermography from the external environment by Sayin et al. (2016), who measured the U value as 2,07±0,38. According to the same study, this difference is possibly due to the use of high-quality concrete with a lower conductivity value than the standards.

Table 2. The thermal characteristics of the opaque materials in the energy models

Building Element	**Material**	**Thickness (mm)**	**ALTERNATIVE 1: Theoretical U value (W/m2-k)**	**ALTERNATIVE 2: Calculated U value (W/m2-k)**
Wall	Concrete, cast-dense, reinforced	250	**3.316**	**2.0**
Roof	Concrete, Reinforced	130	0.577	0.577
	Waterproofing membrane	-		
	XPS - CO2 blowing	50		
	Roofing felt	4		
	Stone chipping	10		
Floor	Ceramic floor tiles	20	2.840	2.840
	Cast Concrete, Dense	80		

The performance metrics are operative temperature, heating energy use and conductive heat loss through the external wall surfaces. We evaluate the percent change in these metrics from the theoretical to calculated R-valued models. The results indicate that the use of calculated R-values have varying degrees of influence (Table 3, Figure 9). The total heat loss through the envelope for the given week has decreased by 9.88%, due to the lower heat transfer rate through the surface. As a result, a decrease of 12.27% in the heating energy use was observed.

Table 3. The results of the energy simulations for the two models

	Total Heating (KW)	**Total Heat Loss through Enve. (KW)**	**Total Heat Loss through walls (KW)**	**Average Oper. Temp (C)**
Simulation with Theoretical U values	1132.50	1552.80	-454.40	18.33
Simulation with Calculated U values	993.50	1399.40	-264.90	18.49
% Change	12.27	9.88	41.70	0.83

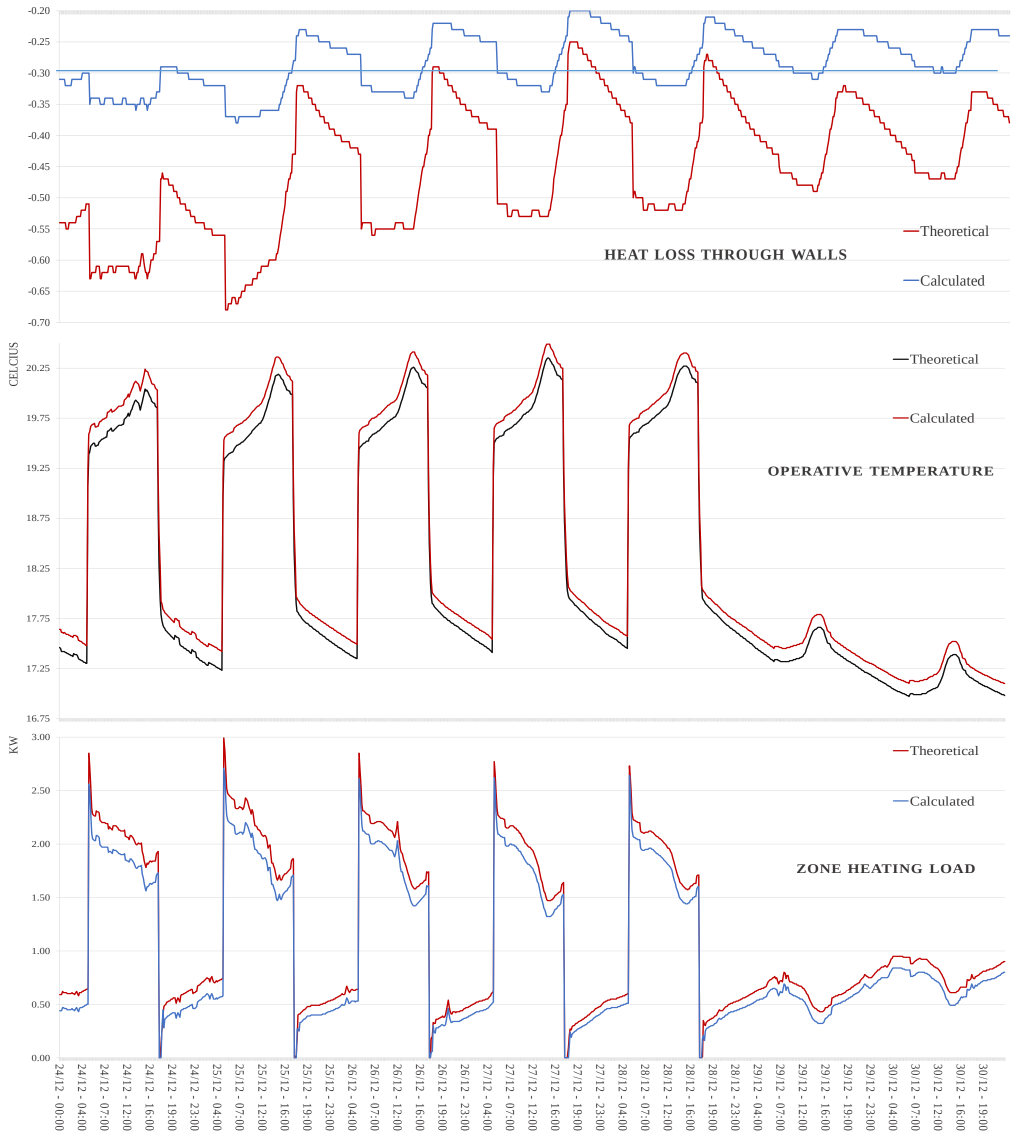


Figure 9. Evaluation metrics for building energy performance (24-30 December)

4. Conclusion

This paper proposed a pipeline for semi-automated energy modeling of existing buildings using 3D reconstruction. The pipeline was evaluated in a room, wherein the electrooptic images, thermal images and the environmental conditions (room and outside it temperature, reflected temperature) were first captured. Two comparative analyses were carried out to evaluate the precision of the 3D model and the level of impact of the newly calculated thermal transmittance value of the external wall on energy performance metrics. Although the building proportions and surface angles are within tolerable limits (<2), the calculated model scale is smaller than the actual dimensions. This is believed to be due to the imprecision in user's selection on digital images. The calculated U value, on the other hand, is %40 lower that the theoretical value of a wall with the same thickness and material. However, our results are consistent with a previous study conducted on the same building wall. The building energy simulations based on the energy models were evaluated through several building performance metrics. The results show that the calculated U-value of the external wall has a considerable influence on these metrics as compared to the theoretical U-value due to the reduced heat loss through the walls. The proposed pipeline is currently being implemented into a proof-of-concept software tool. In the future, tests will be made that involve the identification and registration of the windows and doors onto the walls, and the modeling of multiple adjacent rooms.

Acknowledgements

The authors would like to acknowledge the support by the TUBITAK-British Council's Newton – Katip Celebi Fund, Grant No. 217M519.

References

Akinci, B., Boukamp, F., Gordon, C., Huber, D., Lyons, C., & Park, K. (2006). A formalism for utilization of sensor systems and integrated project models for active construction quality control. *Automation in Construction*, *15*(2), 124–138. https://doi.org/https://doi.org/10.1016/j.autcon.2005.01.008

Bosché, F., & Guenet, E. (2014a). Automating surface flatness control using terrestrial laser scanning and building information models. *Automation in Construction*, *44*, 212–226. https://doi.org/https://doi.org/10.1016/j.autcon.2014.03.028

Bosché, F., & Guenet, E. (2014b). Automating surface flatness control using terrestrial laser scanning and building information models. *Automation in Construction*, *44*, 212–226. https://doi.org/10.1016/j.autcon.2014.03.028

Bosché, F., Guillemet, A., Turkan, Y., Haas, C., & Haas, R. (2013). Tracking the Built Status of MEP Works: Assessing the Value of a Scan-vs.-BIM System. *Journal of Computing in Civil Engineering*, *28*. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000343

Cheng, J., Leng, C., Wu, J., Cui, H., & Lu, H. (2014). Fast and Accurate Image Matching with Cascade Hashing for 3D Reconstruction. In *2014 IEEE Conference on Computer Vision and Pattern Recognition* (pp. 1–8). https://doi.org/10.1109/CVPR.2014.8

Dimitrov, A., & Golparvar-Fard, M. (2014). Vision-based material recognition for automated monitoring of construction progress and generating building information modeling from unordered site image collections. *Advanced Engineering Informatics*, *28*(1), 37–49. https://doi.org/https://doi.org/10.1016/j.aei.2013.11.002

Furukawa, Y., & Ponce, J. (2010). Accurate, dense, and robust multiview stereopsis. IEEE transactions on pattern analysis and machine intelligence, 32(8), 1362-1376.

Ham, Y., & Golparvar-Fard, M. (2013). An automated vision-based method for rapid 3D energy performance modeling of existing buildings using thermal and digital imagery. *Advanced Engineering Informatics*, *27*(3), 395–409. https://doi.org/https://doi.org/10.1016/j.aei.2013.03.005

Hensen, J., & Lamberts, R. (2011). Introduction to building performance simulation. *Journal of Physics D-Applied Physics - J PHYS-D-APPL PHYS*.

Lowe, D. G. (2004). Distinctive Image Features from Scale-Invariant Keypoints. *International Journal of Computer Vision*, *60*(2), 91–110. https://doi.org/10.1023/B:VISI.0000029664.99615.94

M. A. Fischler, R. C. B. (1981). Random Sample Consensus: A Paradigm for Model Fitting with Applications to Image Analysis and Automated Cartography. *Communications of the ACM*, *24*, 381–395.

Mahdavi, A. (2001). Simulation-based control of building systems operation. *Building and Environment*, *36*(6), 789–796. https://doi.org/https://doi.org/10.1016/S0360-1323(00)00065-2

Mahdjoubi, L., Moobela, C., & Laing, R. (2013). Providing real-estate services through the integration of 3D laser scanning and building information modelling. *Computers in Industry*, *64*(9), 1272–1281. https://doi.org/https://doi.org/10.1016/j.compind.2013.09.003

Moulon, P., Monasse, P., & Marlet, R. (2012). Adaptive Structure from Motion with a contrario model estimation 1 Introduction 2 Structure from Motion the classical pipeline. *Lect. Notes Comput. Sci. (Including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, *7727 LNCS*(PART 4), 1–14. https://doi.org/10.1007/978-3-642-37447-0{_}20

Moulon, P., Monasse, P., Perrot, R., & Marlet, R. (2017). OpenMVG: Open Multiple View Geometry BT - Reproducible Research in Pattern Recognition. In B. Kerautret, M. Colom, & P. Monasse (Eds.) (pp. 60–74). Cham: Springer International Publishing.

Sayin, M., Tavukcuoglu, A. (2016). Cephelerin Isi Yalitimlilik Durumlarinin Isil Görüntüleme İle Değerlendirilmesi. Yalitim, Is Dunyasi Yayincilik, Istanbul.

Sweeney, C. (2015). Theia multiview geometry library: Tutorial & reference. University of California Santa Barbara.

Valero, E., Adan, A., & Cerrada, C. (2012). Automatic Method for Building Indoor Boundary Models from Dense Point Clouds Collected by Laser Scanners. *Sensors (Basel, Switzerland)*, *12*, 16099–16115. https://doi.org/10.3390/s121216099

Wang, S., Yan, C., & Xiao, F. (2012). Quantitative energy performance assessment methods for existing buildings. *Energy and Buildings*, *55*, 873–888. https://doi.org/https://doi.org/10.1016/j.enbuild.2012.08.037

Weaver, E., Long, N., Fleming, K., Schott, M., Benne, K., & Hale, E. (2019). Rapid Application Development with OpenStudio: Preprint.

Winkelmann, D. B. C. and C. O. P. and L. K. L. and F. C. (2000). EnergyPlus: Energy Simulation Program. *ASHRAE Journal*, *42*, 49–56.

Developing a Handover Information Exchange Specification between Construction and Asset Management for Road Networks

Rakesh Perumpilly[1], Russell Kenley[1, 2], Toby Harfield[1, *], Michael Niestroj[3], Petra Helmholz[3], Robin Drogemuller[4]
[1] Swinburne University of Technology, Melbourne, Australia
[2] Unitec Institute of Technology, Auckland, New Zealand
[3] Curtin University, Perth, Australia
[4] Queensland University of Technology, Brisbane, Australia
* email: tharfield@swin.edu.au

Abstract

This desktop review of road asset management information requirements at the handover phase of construction studies the different needs of vertical and horizontal infrastructure. The paper considers three specifications for construction information at handover to asset management. COBie (Construction to Operations for Building information exchange), and the proposed CONie (Construction to Operations for Network information exchange). COBie has been successfully used for vertical construction since 2007, but the specification was not intended for use in road construction. However, the UK drive to introduce digital information exchange for all new government projects resulted in in an attempt to development a hybrid COBie-for-All specification to include both vertical and horizontal infrastructure. However, differences in definitions and utilization of data linked to specific attributes, such as location, cannot be force fitted into a dual-use information exchange specification. Thus, the development of a single-use specification intended for horizontal network assets is deemed the only logical option. That is the purpose of the CONie research project into the development of a handover specification to meet the needs of asset management of a number of road authorities from Australia and New Zealand.

Keywords: Handover, COBie, CONie, road networks, road assets

1. Introduction

As part of the drive for governmental efficiency, in some countries, the use of building information modelling (BIM) has been mandated for public works, for example, Britain, Singapore, Japan, and Malaysia (UK NBR, 2019; Kaneta et al., 2016; Latiffi et al., 2013). This is because the concept of Integrated Project Management (IPM) suggests a value-add is gained by sharing and exchanging information utilising a Building Information Modelling (BIM) environment (Kent & Becerik, 2010).

It has also been suggested that IPM (Rowlinson, 2017) is the obvious solution for one of the handover bottlenecks in the construction process. However, advent of digital technology has not diminished the massive amounts of project information. This is especially true for the data that is useful input into facilities management systems. COBie (*Constructions to Operations Building information exchange*) was developed to rectify the problem by simplifying the process (East, 2007). COBie, as the name suggests, was specifically designed to focus on the asset management for buildings.

The COBie specification was developed in the USA as a part of their contribution in the global standardization effort for Integrated Project Delivery for vertical infrastructure (Rowlinson, 2017; Cerovsek, 2011). During the development of COBie, facilities managers (the expected end-users), explained to the specification developers the types of information they need to manage their assets (East, 2007). This bottom-up approach to research (Tan et al., 2018) meant that parameters for the facilities management specification led to functionality in BIM enabling systems for vertical infrastructure (UK NBR, 2019).

However, what was missing from that research into the needs of asset end-users, was input from network asset managers. Obviously, a handover specification developed for horizontal infrastructure assets, such as roads or utilities, could provide the same value-add as COBie does for vertical infrastructure.

It makes sense to learn from the COBie specification development project. For example, in the design of a *construction to operations for network information exchange* (CONie) it is important to ask end-users what handover information will enable effective network asset management. In addition, modelling a new information exchange on contract conditions as set out in COBie, can establish constraints. These fundamentals are, therefore, built into the design a network handover specification that is being developed in an Australian government funded research project with road authorities in Australia and New Zealand (Kenley & Harfield 2018; Kenley & Harfield 2016).

This paper outlines the fundamental differences between construction information required at handover for COBie and for the proposed CONie. The structure of this paper begins with details of the research design in section two. Section three explains some COBie specification attributes for buildings. Section four focuses on the lack of development of a proposed COBie-for-All that was expected to also be useful for road network assets. Section five discusses the need for an information exchange for horizontal infrastructure. CONie, a proposed information exchange for road networks, is outline in Section six, followed by the Conclusion.

2. Research Design

The purpose of this historical desktop research is to explore both the development of COBie (vertical infrastructure) and the rationale for the proposed CONie (horizontal infrastructure). The development of the BIM concepts, standards and specifications is the topic of a large range of documents from a variety of points of view. For this project, a limited number of seminal references plus those that feature COBie were considered relevant.

Thus, a three stage analytical document content review method was used (Fielding, 2008).

2.1 Stage one

Online (open access) and university library (limited access) resources were employed as possible datasets. Documents found included: academic journal articles, academic conference papers, government reports, international standards, and industry research publications. Presentations or talks were excluded because of the access limitations.

The first search terms were: COBie and BIM. The search was initially incorporated to publications between 1990 and 2007. IPD was suggested in 1990 and 2007 was the year COBie specification was accepted (East, 2019).

2.2 Stage two

The search was extended to include 2008-2019 in order to find additional documents about COBie. Although developers of BIM environments claim COBie is integrated into 170 software programs, little academic literature was found (Zhao, 2017; Kaneta et al., 2016; Becerik-Gerber et al., 2011). However, industry research reports and guidelines for BIM implementation for these later dates, often includes COBie usage and/or recommended modifications (ABAB, 2018; Hampson et al., 2018).The stage two search also included new search terms COBie-for-All and CONie (*Construction to Operations for Networks information exchange*). However, only a small subset of items were found (Kenley & Harfield, 2016; Scarponcini et al., 2013).

2.3 Stage three

Stage three was a systematic review of a documents containing text related to COBie, COBie-for-All, and CONie. The review was only to verify that the documents actually discussed, in some detail, these three types of digital information exchange.

Themes were then created from substantive texts. Three common themes found are: the development of COBie as part of the Industry Foundation Classes, the continuing problems of information exchange interoperability for BIM environments, and the differences between vertical and horizontal infrastructure asset data needs.

3. COBie: Asset Handover Specification for Vertical Infrastructure

3.1 Analytical document content review

The historical desktop review was not able to find a significant number of research reports on the use of COBie. The academic and industry journals seem to be limited to a small number of articles by the specification developers. Internet webpages also provide commentary and access to the open source standards and specifications. Government reports and working papers related to BIM are mostly aspirational rather than substantive. The monitoring reports for BIM implementation in the UK (UK NBR, 2017) provides an example:

> *"The vision of the UK being the world leader in BIM has yet to be realised, according to the design community. Only 19% agree that we are the world leader. Perhaps the Government set the bar a little high?"*

More importantly, for this study, the annual survey does ask questions about the use of COBie. Although the reports does not provide extensive data about respondents, in the 2018 report, 41% of the 808 respondents used COBie to provide an 'output' for asset management. (UK NBR, 2018).

At the same time, although the COBie specification was completed in 2007, research using the specification was only found in two industry reports. Examples of substantive text from these research reports were not based on simulations. Akhurst (2017) used Australian data from the Queensland Department of Works public housing database:

> *"An important principle in the use of COBie is to maintain the structure of the COBie asset data tables so that the methodology can be applied repeatedly across many and varied projects and assets. The case study found that the housing asset information did not readily align with the generic COBie workbook tables. The housing asset information has evolved over many years and is structured in a manner that on occasions combines type, component, space, facility and other information in a manner that must be deconstructed to achieve alignment with the COBie tables."*

In a second report Hampson et al. (2018) reported on a multi-residential housing project in Toowoomba, Australia. They conclude:

> *"The feasibility of bringing the model directly into an asset management system was tested using the COBie export utility for the Autodesk Revit software. The original naming conventions and attribute policies within the BIM model did not conform to the COBie standard. However, minor editing of the relevant families (object definitions) within Revit led to successful export of valid COBie files. These could then be imported directly into a COBie-conformant asset management system."*

3.2 Development of a speciation

buildingSMART international (Jackson, 2018) has developed definitions for Building Information Modelling based on object libraries and International Foundation Classes standards (Eastman et al., 2008). The international standard, ISO16739, specifies a conceptual data schema and an exchange file format for BIM data (ISO16739, 2013). IFC2 was initially developed for vertical infrastructure in which COBie is a subset. COBie specification defines a precise set of information needed to solve a specific problem at a specific point in the construction life cycle: handover (East et al., 2015).

Traditionally, the facility management information has been created after construction is completed. All project paper materials (drawings, manuals, schedules, etc.) were delivered to the facility owner/operator (East et al., 2015). However, ominously large amounts of these types of information were not necessary for building asset management operations.

The problem is the same with the increasing use of digital modelling, devising a method for managing the large amounts of digital materials at the handover phase (East, 2019). Thus, the solution of a COBie information exchange format. COBie extracts the required asset information from an IFC schema by transporting it into a standard COBie schema, making it ready to import into a digital facility management system.

4. COBie-for-All: Handover for Buildings and Roads

4.1 Analytical document content review

COBie for All: Required Information for Facility Ownership Buildings & Civil/Infrastructure, Understanding How COBie Works in the UK Infrastructure Market (Scarponcini et al., 2013). This report outlines problems that arise when the requirements of a handover specification designed for vertical infrastructure and conflated with the needs of horizontal infrastructure asset management

4.2 Development of a speciation

In May 2011, the UK government published the *Government Construction Strategy* paper (UK Cabinet Office, 2011), announcing the intention of requiring Level 2 Building Information Modelling by 2016 for all government infrastructure projects. This meant use of digital collaborative 3D BIM for all project and asset information and documentation.

Both the UK drive to introduce digital information exchange for all new government projects and the lack of interoperability between object-based design (vertical infrastructure) and string-based design (horizontal infrastructure) was the business case for the development of a new COBie-for-All specification. Based on the initial studies conducted between 2011 and 2013, a draft report was released for public comment on 15 October 2013 (Scarponcini et al., 2013).

The title of the document provides a simple explanation of the contents:

> *"COBie for All: Required Information for Facility Ownership Buildings & Civil/Infrastructure, Understanding How COBie Works in the UK Infrastructure Market."*

Clearly this 60-page manual of 'problems' and 'solutions' aims to stretch the initial COBie specification for buildings to include network assets such as roads.

However, the UK BIM Task Force that developed strategies to continue British development of the COBie-for-All information exchange has since been disbanded. All online searches for BIM Task Force documents is now referred to the UK government funded Centre for Digital Built Britain at the University of Cambridge (CDBB, 2018).

In the first CDBB major review of information exchange structures COBie and IFC are considered, but not COBie-for-All. Currently, the COBie-for All (Scarponcini et al., 2013) is not available from an online open access repository.

However, personal communication in 2018 with British contractors tendering for government road infrastructure, indicates they have not been required to use COBie-for-All. Therefore, it must be assumed that the development of a vertical/horizontal infrastructure information exchange specification is no longer being developed. Clearly, one shop does not suit every type of construction project (Pärn et al., 2017).

Yet, the global drive to increase the implementation of BIM platforms continues. Thus, the continuing need for a horizontal infrastructure specific digital information exchange specification (Kenley & Harfield, 2016).

5. Why We Need a Network Information Exchange

5.1 Analytical document content review

Little was found about CONie (*Construction to Operations for Network information exchange*). Currently it remains a 'concept' because this proposed information exchange open specification is still in the early stages of development.

5.2 Development of a speciation

Handover is the set of all documents that must be provided by the contractor (East, 2019). However, horizontal infrastructure projects have the same problem as vertical infrastructure projects. Even with IPD, by the end of construction many types of documents will have accumulated, and not all of them will have information useful to road asset managers. COBie is the handover solution for vertical infrastructure.

But, currently there is no handover information exchange specification that can be used effectively by road asset management systems. For example, The software AutoCAD Civil 3D from the company Autodesk ('http://www.autodesk.com') is a tool to design road networks with the support of BIM. The IFC 4 and IFC 4x1 support has been implemented in Civil 3D with the update 2018.1. The update adds the functionality to import/export alignments and profiles (Autodesk, 2017). However, the IFC Alignment solution only supports the design phase not the handover phase. Therefore, it is important to develop a *Construction to Operations for Networks information exchange* (CONie) handover specification to assist asset managers for the horizontal infrastructure. The desired outcome is to transform the data sets more easily from one program into another without information loss so that the existing databases can be both supplemented or adapted.

Road asset management includes several different types of systems. For example, Their road project data are usually produced with software such as 12d, AutoCAD or Bentley, and lacks an export functionality to asset management systems. To ensure best practice and code compliance, road authorities have access to extensive technical libraries of standards and references for regional or national standards. This means that road asset systems utilise several different types of management resources.

To capture this complexity the development of an information exchange specification, needs to consider five types of information:

- Systems: An interconnected network of road resources of specific types, typically defined by number of lanes and median type, and managing jurisdiction.
- Projects: A set of work with a defined start and end. Projects require engineering plans and specifications that are executed by either road authorities or contractors.
- Jobs: A recurring set of projects needed to keep the network operating at appropriate levels of performance. Jobs typically do not require engineering plans and specifications that are based on standards-of-practice.
- Resources: A set of tools, materials, labor, and training needed to perform jobs that can be internal or external to a road authority thus, requiring knowledge of how to transfer the information that might be useful for asset management functionality.

- Standards: A set of templates for roadway profiles (and associated assets) and jobs, as well as engineering details necessary to insure consistency of projects within the network. Specific departments within a road authority usually can develop standards for processes, products and information. In addition, national or international standards can in applied as they are developed or revised.

Thus, the data format must have generally applicable business rules, and sample data in a format that respects those rules. To be successful in developing CONie it is necessary to apply the lessons learned from the development of COBie (East et al., 2015).

6. Conclusions

The use of building information modelling (BIM) has been mandated for public works as part of the drive for governmental efficiency. The concept of Integrated Project Management suggests sharing and exchanging information utilizing a BIM environment adds value. Thus, BIM is expected to eliminate the information exchange bottleneck, construction handover to asset management.

Therefore, this desktop review has provided a comparison of three related information exchange specifications for construction information at handover to asset management. COBie (*Construction to Operations for Building information exchange*), COBie-for-All and the proposed CONie (*Construction to Operations for Network information exchange*).

Although COBie has been available since 2007 to be used as part of the IFC structure for integrated project delivery, little published research is available. Of the many governments mandating the use of BIM, only the UK has attempted to modify the original use of COBie to include both vertical and horizontal infrastructure. However, development of this hybrid, COBie-for-All specification, has been abandoned.

The only proactive account of designing a specific handover specification for horizontal rather than vertical infrastructure is from road authorities in Australia and New Zealand. They are currently working on a CONie that takes into account the network requirements for asset management. Their solution is expected to be the development of a handover specification intended for use in road asset management systems.

Acknowledgements

The authors would like to acknowledge the support by the Australian Research Council, Grant No. LP116100524 and Austroads, Grant No. ASP2112. Appreciation to Bill East for his contribution.

References

ABAB (Australasian BIM Advisory Board) (2018) Asset Information Requirements Guide: Information required for the operation and maintenance of an asset. Online 15Apr19 http://www.abab.net.au/wp-content/uploads/2018/12/ABAB_AIR_Guide_FINAL_07-12-2018.pdf

Akhurst P (2017) Using *COBie with existing housing asset information. Case Study Report.* Project 2.46 Whole-of-life Value of Constructed Assets through Digital Technologies. Perth, Australia, Sustainable Built Environment National Research Centre. Online: 15Apr19 https://sbenrc.com.au/app/uploads/2018/09/P2.46HousingCaseStudy-FINAL.pdf

Becerik-Gerber B, Jazizadeh F, Li N & Calis G (2011) Application areas and data requirements for BIM-enabled facilities management. *Journal of Construction, Engineering and Management, 138*, 431-42

CDBB (Centre for Digital Built Britain) (2018) L2C PR OGRAMME Standards landscape and information management systems WP4: Comparison of COBie and IFC as information exchange structures today and in the future V2.0 – Issued. Online: 15Apr19 https://www.cdbb.cam.ac.uk/Resources/ResoucePublications/CDBBL2CWP4ReportLRCOBieIFC_V2.0_finalissue.pdf

Cerovsek T (2011) A review and outlook for a 'Building Information Model' (BIM): a multi-standpoint framework for technological development. *Advances in Engineering, Inform. 25,* 224-44.

East B (2019) *Construction-Operations Building information exchange (COBie) Whole Building Design Guide* Online: 15Apr19 http://www.wbdg.org/resources/construction-operations-building-information-exchange-cobie

East B, Kenley R & Harfield T (2015) *CONie: lessons to be learned from COBie specifications and standards.* SBEnrc Project 2.33 New Project Management Structures Briefing Paper. Perth, Australia: Sustainable Built Environment National Research Centre. Online: 15Apr19 https://researchbank.swinburne.edu.au/file/ac93cdf6-63ee-4715-9b73-94f477a67f58/1/2015-east-conie-lessons-to.pdf

East EW (2007) *Construction operations building information exchange (Cobie): requirements definition and pilot implementation standard*. Construction Engineering Research Laboratory TR-07-30 ERDC/CERL. Champaign IL: US Army Corps of Engineers, Engineer Research and Development Center. Online: 15Apr19 https://apps.dtic.mil/dtic/tr/fulltext/u2/a491899.pdf

East EW, Nisbet N & Liebich T (2013) Facility management handover model view. *Journal of Computing for Civil Engineering, 27,* 61-67.

Eastman C, Teicholz PR, Sacks R & Liston K (2008) *BIM handbook: A guide to building information modelling for owners, managers, designers, engineers, and contractors.* New Jersey: John Wiley and Sons, Inc.

Fielding NG (2008) *The SAGE handbook of online research methods.* ebook: Sage Publications Online 15Apr19.

Hampson, K, Wang, J, Wu, P, Drogemuller, R, Omrani, S & Shemery, A (2018) *Digital Asset Information Management (DAIM): A Guide and Manual, Final Industry* Report. Project 2.51: Developing a Cross-sector Digital Asset Information Model Framework for Asset Management. Perth, Australia, Sustainable Built Environment National Research Centre. (in Press)

ISO16739 (2013) *Industry Foundation Classes (IFC) for Data Sharing in the Construction and Facility Management Industries*. (Online: International Standards Organization)

Jackson P (2018) Infrastructure Asset Managers BIM Requirements Technical Report No. TR 1010, v1. Online: 15Apr19 https://www.buildingsmart.org/wp-content/uploads/2018/01/18-01-09-AM-TR1010.pdf

Kaneta T, Furusaka S, Tamura T & Deng N (2016) Overview of BIM implementation in Singapore and Japan. *Journal of Civil Engineering and Architecture, 10,* 1305-12

Kenley R & Harfield T (2016) *Location Importance in Infrastructure: New Project Management Structures*. SBEnrc Project 2.33. Sustainable Built Environment National Research Centre, Perth. Online: 15Apr19 https://researchbank.swinburne.edu.au/file/7622045a-19fd-4dac-9e5d-1d44252375ca/1/2016-kenley-location_importance_in.pdf

Kenley R & Harfield T (2018) *Scoping Study for a Location Referencing Model to Support the BIM Environment.* Austroads Research Report AP-R568-18.Sydney, Australia: Austroads.

Kent DC & Becerik-Gerber B (2010) Understanding construction industry experience and attitudes toward Integrated Project Delivery. *Journal of Construction, Engineering and Management, 136*, 815-25

Latiffi AA, Mohd S, Kasim N, & Fathi MS (2013) Building Information Modeling (BIM) application in Malaysian construction industry. *International Journal of Construction Engineering and Management, 2,* 1-6.

Pärn, EA, Edwards, DJ & Sing, M C P (2017) The building information modelling trajectory in facilities management: A review. *Automation in Construction, 75*, 45–55.

Rowlinson, S (2017) Building information modelling, integrated project delivery and all that. *Construction Innovation, 17*, 45-49.

Scarponcini P, et al. (2013) *COBie for All Required Information for Facility Ownership Buildings & Civil/Infrastructure: Understanding how COBie works in the UK infrastructure market.* London: BIM Task Group.

ISO19148 (2012) *Geographic Based Information-Linear Referencing.(* Online: International Organization for Standardization)

UK NBR (2017) *National BIM Report*. Royal Institute of British Architects. Online: 15Apr19 https://www.thenbs.com/knowledge/nbs-national-bim-report-2017

UK NBR (2019) *National BIM Report.* Royal Institute of British Architects. Online: 15Apr19 https://www.thenbs.com/knowledge/nbs-national-bim-report

UK Cabinet Office (2011) G*overnment Construction Strategy*. Online: 15Apr19 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/61152/Government-Construction-Strategy_0.pdf

Tan AZT, Zaman A & Sutrisna M (2018) Enabling an effective knowledge and information flow between the phases of building construction and facilities management. *Facilities, 36*, 151-170.

Zhao X (2017) A scientometric review of global BIM research: analysis and visualization. *Automation in Construction, 80,* 37-47.

Linked-data based dynamic constraint solving framework to support look-ahead-planning in construction

Ranjith K. Soman,
Centre for Systems Engineering and Innovation, Imperial College London, United Kingdom
The Alan Turing Institute, United Kingdom
email: ranjithks17@imperial.ac.uk

Abstract

This paper presents a framework for solving dynamic constraints to aid the automation of look ahead planning. The constraints in construction processes are highly dynamic and complex with numerous interdependencies, making it difficult to be modelled using relational databases or similar informational models. Recent research has used linked-data based modelling approaches to address this issue. Linked-data enables linking of data across domains and heterogeneous sources, without being limited by the underlying schema. This addresses the problem of complexities and interdependencies in construction constraints. Although there is extensive research done on linked-data applications to address the limitations of current information modelling approaches in the constructions sector, the focus has been on the modelling of product information. Applications of linked-data to address the limitations in information models for representing process information such as constraints relationships and resource dependencies are relatively less explored. Building on the research on linked-data in the construction sector, this paper presents a framework for dynamic constraint solving using linked-data and Shapes Query Language (SHACL) to address this limitation. The process information is modelled in Resource Description Framework (RDF) on top of the ifcOWL ontology, and constraints are modelled in SHACL. A prototype is developed based on the framework presented, which uses a python server to process the constraints modelled in SHACL. The prototype validates the process information in the model, against the modelled constraints to check whether a schedule is feasible or not. This framework can be used to automate look-ahead-planning in construction.

Keywords: Linked-data, SHACL, constraints, dynamic constraint solving

1. Introduction

The construction sector is undergoing rapid digitization caused by the introduction of Building Information Modelling (BIM) , advancements in Information and Communication Technologies (ICT) (Alsafouri & Ayer, 2018), policy level interventions such BIM mandate in the UK (Waterhouse et al., 2016), etc. The digitization in the sector has transformed how the computers are used in the sector form being disconnected tools to being an integral part of the workflows and augmenting the daily activities. This has resulted in the generation of massive amounts of data from the projects (Anumba, Bouchlaghem, Whyte, & Duke, 2000; Whyte, Stasis, & Lindkvist, 2016). The huge volume of information generated offers the possibilities for implementing advanced decision support tools utilizing the state of the art in machine learning. Building on these developments in computing, the construction sector is moving towards agile and real-time project management practices to improve efficiency and performance (Levitt, 2011; Whyte & Levitt, 2011).

Despite having generated huge volumes of information, there are inherent problems within the generated data which limits the application of data science to support decision making, especially due to the quality of data. Bilal et al. (2016) had surveyed the Big Data techniques in the context of construction and has raised the issue of low data quality in construction data. Also, previous research in the area has reported the lack of process level information codification. Although, 4D BIM has led to the codification of task sequences and their relationships to BIM objects (Huhnt, Richter, Wallner, Habashi, & Krämer, 2010; Subramanian, Songer, & Diekmann, 2000), Han & Golparvar-Fard (2017) has reported that the data in these 4D models lack the detail in work break down structure to match the operational details. Also, the tasks lack detailed semantics (such as the relationship between tasks, resources and constraints) leading to the nonexistence of linear dependence between resources employed and work progress (Giretti, Carbonari, Novembri, & Robuffo, 2012). Lack of detail and semantics in process information hinders the opportunities offered by the fourth industrial revolution to make the construction process management agile.

To address the issues of lack of detail and semantics, there exists a need to codify the relationships between tasks, resources and constraints in detail. However, the constraint relationship has inherent dynamicity and uncertainty limiting the users from coding them using the conventional BIM tools. BIM tools lack the ability to code these relationships in a dynamic nature as the relationships are complex and spanning across different domains (anecdotal evidence from observing BIM use in projects). This paper addresses this issue (lack of detail and semantics in the process information) by presenting a framework using Shapes Constraint Language (SHACL) and linked data principles to code complex constraints and performs dynamic constraint solving to support look ahead planning. Rest of the paper is divided into six sections. Section 2 provides background on the Linked Data and SHACL and section 3 explains the research method in brief. Section 4 presents the constraint validation framework and Section 5 presents a prototype implementation of the framework. Section 6 discusses the results from prototype testing and Section 7 presents the conclusions from this research.

2. Background

2.1 Linked data

Linked data is a method of publishing and interlinking structured information on the web (Bizer, Heath, & Berners-Lee, 2009) following the principles stated by Berners-Lee (2006). In Linked data, information artefacts are modelled as ‘concepts’ and related to associated ‘properties’ in the form of a statement. Each statement (called as triples) has three resources which are subject, predicate and object. Multiple triples are combined in the form of a graph where subject and object resources form nodes while predicates form edges of the graph (Pieter Pauwels, McGlinn, Törmä, & Beetz, 2018).The main principles of publishing information using linked data are 1) Use Uniform Resource Identifiers (URI) to name the resources (both concepts and properties) 2) Use HTTP URI, so that the modelled resources can be accessed using internet 3)Provide more information about the resources using standards (RDF,SPARQL) when the URIs are looked up and 4) Providing links to the related URIs so that the resource can act as a starting point to explore the related data spaces (Berners-Lee, 2006). These principles enable Linked-data technologies to link and share data across heterogeneous sources without being limited by the scope of underlying schemas of the source data (Zhang & Beetz, 2016).

P. Pauwels, Zhang, & Lee (2017) have surveyed the application of Linked Data in the AEC domain. Researchers have attempted to use linked data to address the limitations of BIM related to structuring and querying product information (Beetz, Van Leeuwen, & De Vries, 2009; Liu, Lu, & Al-Hussein, 2016; Zhang & Beetz, 2016), facility management (Kim et al., 2018; Terkaj, Schneider, & Pauwels, 2017), solving interoperability (Pieter Pauwels, De Meyer, Van Campenhout, Meyer, & Campenhout, 2010) etc. Although limitations of the use of BIM tools during the construction stage leading to semantic and detailed process informaiton can be achieved using linked data (by linking data across domains and using logical inferencing), it is relatively less explored.

2.2 Shapes Query Language (SHACL)

Shapes Constraint Language (SHACL) is a data modelling language to model constraints against which a linked data modelled as Resource Description Framework (RDF) could be validated (Knublauch, Allemang, & Steyskal, 2017). Validating an RDF model with a set of constraints using SHACL addresses the inherent issue of open world assumption in RDF graph as SHACL offers the opportunity to define structural constraints (Ekaputra & Xiashuo Lin, 2016). SHACL has two components, a data graph and a shapes graph. Data graph contains the data to be validated and shapes graph contain constraints against which resources in the data graph are validated. Data graphs and shapes graph may be coded in a single RDF file or multiple RDF files as it is the triples in data graph that is validated against triples in shapes graph. There are two types of shapes in SHACL.; Node shape and Property shape. Node shapes are constraints which acts on subject resources (or concept instances) of a specific type (type can be defined while modelling constraints) in the data graph and the property shapes are constraints which acts on the predicate resources (or attribute instances). SHACL SPARQL is an advanced feature of SHACL which contains all the features mentioned above, and offers the expressive power of SPARQL to target specific instances of a subject resource satisfying certain conditions (flexible to define the conditions) (Knublauch et al., 2017). When a data graph is validated against a shapes graph, all the data instances in the data graph is checked against the applicable shapes in the shapes graph and a validation report (in the form or another RDF graph) is produced, which details the instances which have passed and violated the constraints.

The opportunities offered by linked data to interlink heterogeneous data sets without being limited by the scope of the underlying schema and the SHACL's ability to model constraints spanning domains, enables the modelling of complex constraints necessary for representing detailed and semantic construction process information, addressing the problems in conventional BIM tools. The construction process information can be represented as an interlinked web of data across domains and SHACL constraints act as a model checker for the web of data. This paper presents a framework to achieve such a representation building on the research on ifcOWL and SHACL-SPARQL.

3. Research method

The proposed research followed research methodology comprising of three phases:

1. Investigating the problems with current management practices focusing on the information flow between the design team and the constructing site using the available literature in the area and construction projects in the late design and construction phases. This part of the methodology followed the interpretive case study method (Eisenhardt & Graebner, 2007) and is out of the scope of this paper (will be discussed in detail in a forthcoming paper). However, one of the findings from the study the lack of codification of process information led to the development of the dynamic constraint solving framework.
2. Developing a framework and a prototype for codifying the process information to support look ahead planning drawing insights from the challenges observed in the previous phase of the research.
3. Evaluate the developed framework using a public dataset. The public dataset is enriched with supporting data and test scenarios are generated. Test scenarios are checked using the developed prototype to determine whether the developed prototype can detect constraint violations.

4. Constraint validation framework

The results of examining five construction projects through an interpretive case study method showed the lack of codification of detailed process information and constraints (Forthcoming paper). This finding was also evident in the literature and suggested the development of a framework to codify detailed construction process information and constraints and enable dynamic constraint solving for aiding decision-making during look ahead planning. The framework for solving the dynamic constraints is shown in Figure 1. This framework is intended to be used at the look ahead planning meetings to aid the decision making in the meetings. There are three layers in this framework; 1) User Interface Layer 2) Processing Layer and 3) Ontology layer.

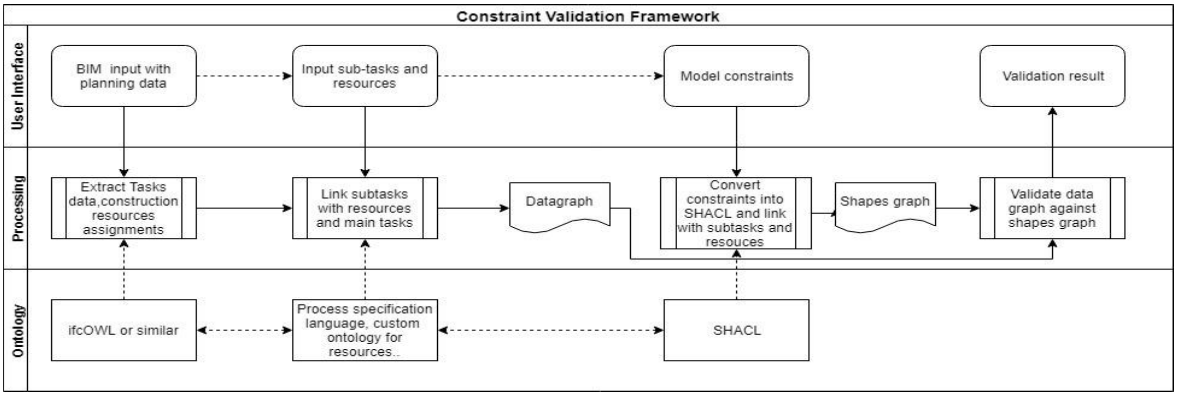


Figure 1: Framework for dynamic constraint solving

1 User interface layer: This layer is for interaction with the user. Hartmann (2008) has stated that the technologies and tools should suite with the existing work practices for successful adaptation. There are three major inputs from the user in this layer. Hence, it is recommended to design the user interface layer as an increment to the current 4D planning user interface. The first input is a BIM model with embedded planning information. This information has the planning data at the master planning/phase planning level. The second input from the user would be the information required to enrich the planning data. The information input would include subtasks for main tasks/activities in the master planning, renewable and nonrenewable resources needed for executing the tasks etc. The third input from the user includes information on constraints, and the relationship between activities, subtasks, resources, approvals etc. The output from this layer is the feasibility report of activities scheduled using the information from the input layer.

2 Processing layer: The second layer in this framework is the processing layer. There are three main processing tasks in this layer. The first task involves extracting the planning data from the BIM model and enriching it with the detailed data input from the user. For extracting the planning data, BIM ontology (eg. ifcOWL or similar) is used. To enrich the data, interlinking is done with the support of the base ontology for the resources and processes (such as process specification language.). This leads to the generation of 'data graph' for the particular look ahead window in RDF. The second task involves creating a Shape graph from the constraint information taken as an input from the user. This task would also import the previous shape graphs generated from the prior meeting. This uses the SHACL ontology. The third task is to validate the data graph against shapes graph to determine the constraint violations is any. This task uses the methodology explained in Soman (2019) to formulate the scheduling constraints and validate them.

3 Ontology layer: This layer holds the schema for different data such as BIM data, resource data SHACL etc. The schemas are stored on the web and published as per the principles stated by Berners-Lee (2006). As this layer is accessed during the execution phase, the latest updates to the ontologies and constraint relationships introduce dynamicity in this framework. Schemas are referenced and not hardcoded. Hence each schema can evolve on its own without the need for related schemas to be altered.

The developed framework has the capability to solve dynamic constraints as the data graph and the constraint graphs exists as separate graphs. The constraints are not hard-coded into the system but can be modelled during the look-ahead planning meeting and edited or appended after that. The modelled constraints apply to the data in the data graph. This enables the capture of knowledge generated during meetings to be codified into a machine-readable format and reused. For example, if constraints related to a resource (say crane) is discussed in a look ahead planning meeting and codified as SHACL constraint. These constraints would automatically be reused in the further meetings automatically even when it is not explicitly mentioned. If not relevant, there are provisions to ignore the constraints.

5. Prototype Implementation and evaluation

A prototype was developed based on the framework discussed in the previous section. The prototype demonstrates the three layers as mentioned in the framework. The prototype was developed as a web application and can be deployed on the cloud. The architecture of the prototype is as shown in Figure 2

User interface (UI) of the prototype was developed in such a way that it could easily integrated into look ahead planning meeting. Hence, a UI similar to that of a 4D planning tool was adopted (refer to Figure 3). UI is created using HTML and CSS as front end, and Javascript as a back end. UI consists of a Gantt chart showing activities for the week and interaction enabled the model view. These activities are derived from the planning data (at master planning level). When you click on an activity, object to which the activity is connected to is highlighted and vice versa. There are options to add subtasks, resources and constraints to the activity. Once these details are added, the validate button checks the data graph created from the user input with the shape graph generated from the modelled constraints to find constraint violation.

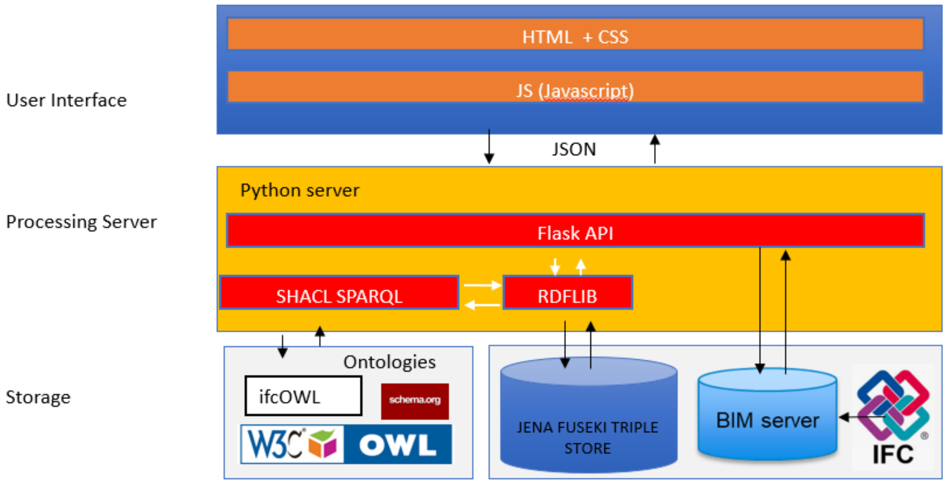


Figure 2:Prototype architecture

The processing server is coded using FLASK API in python. RDFlib library in python is used to process the data modelled in RDF. The constraints modelled are validated using SHACL-SPARQL functions in pySHACL library accessed through python server. The validation results were parsed using RDFLib and the violations if any were reported within the python server. The data is stored in a Jena Fuseki triple store. SPARQL queries to the Jena Fuseki were served over HTTP requests. IFC data in IFC OWL 2x3 is served as the model instance for the process data. To interact with the modelview, IFC open-shell and BIMs erver was used.

The ontology layer was handled through RDFLib. RDFLib accessed the schema definitions over the internet. This was queried to determine the relationship between schema. The main ontologies used for the prototype are OWL ontology, RDFs ontology, RDF ontology, ifcOWL, SHACL and a custom process ontology based on Process Specification Language. As planned model from the dataset Schependomlaan was imported for the testing. The data set had activities in it coded as IFC Tasks class with the schedule information coded into the IFC Schedule Time Control class. Ifc Rel Assigns To Process class connected the particular object instance to the IFC Task class. IFC Rel Sequence defines the precedence relationship of the IFC Tasks For the demonstration of the prototype, Construction resources and subtasks are defined as custom classes Subtask and Resource. Subtasks are assigned to IFC Tasks using sub task of and Resources are assigned to IFC Tasks using resource OF as shown in Figure 4 for this paper. Subtasks are inherited from IFC Tasks The enriched data along with the planning data from the BIM forms the data graph.

The data as given in Table 1 were given as an input to the prototype. The instances for IfcTask class which were enriched can be referenced as Tasks T1 and T2 in this paper. Subtasks for T1 and T2 are S1,S2,S3 and S4,S5,S6 respectively. R1 ,R2,R3,R4 are the resources available to the activities. are

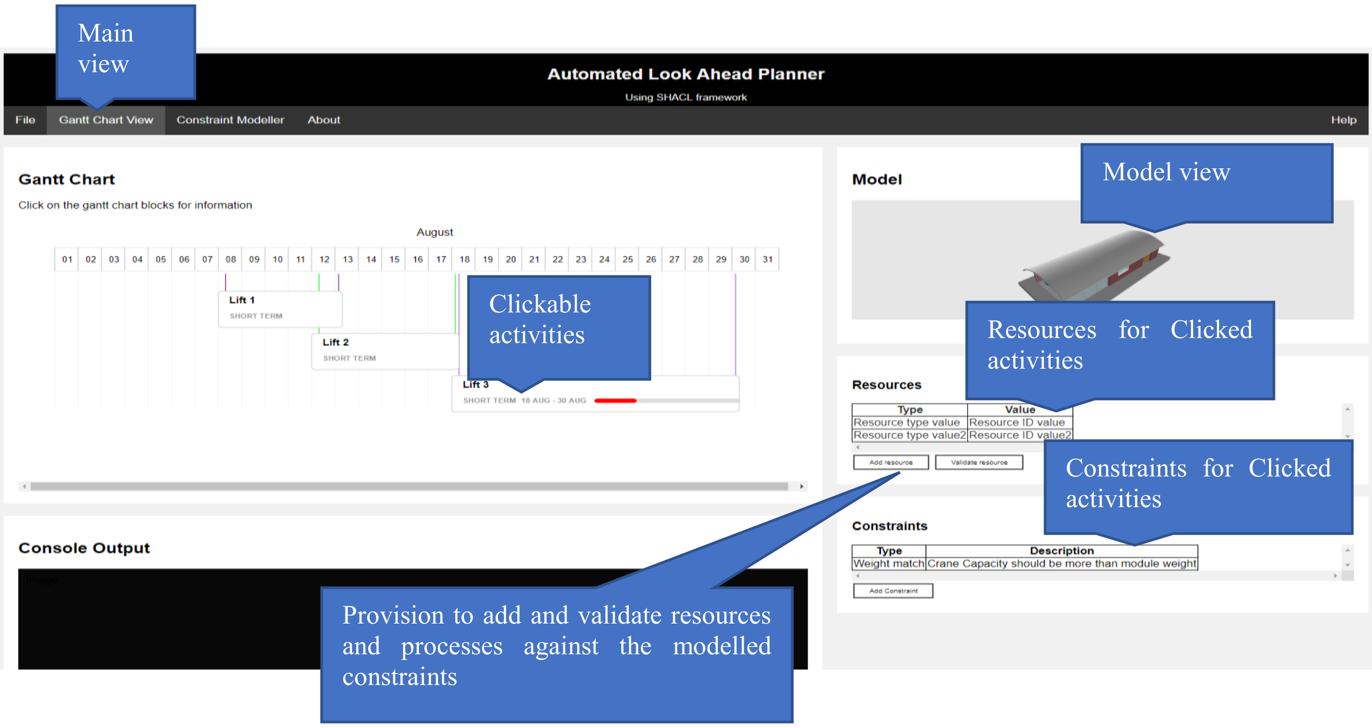


Figure 3: Screenshot of the prototype user interface

the O1 and O2 objects for which tasks and subtasks to be carried out. The detailed inputs were given in two sessions. First session for S1,S2,S3 and second session for S4,S5,S6.

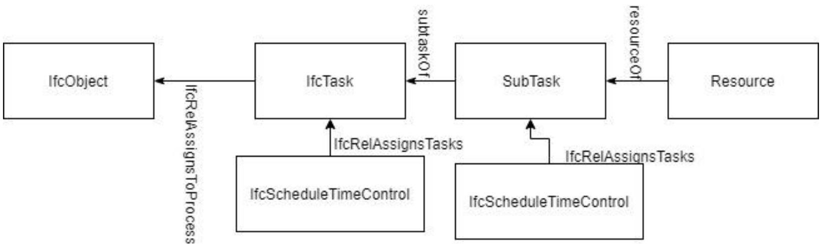


Figure 4: Ontology for linking process information

Input from the users on constraints was used to generate SHACL queries. Precedence and disjunctive constraints as specified in Morkos (2014) were given for the activities. S1,S2,S3 had a start to finish relationship as precedence constraint (meaning S1 happens first followed by S2 and finally S3). Similarly S4,S5,S5 had start to finish relationship. Also the resources R1,R2,R3 and R4 were assigned the disjunctive property. This means that they can not be shared between activities. The collection of the SHACL queries formed the shapes graph. During the validation Data graph generated were checked against constraints modelled in the Shapes graph to find the constraint violation.

Table 1: Input data for generating the data graph

SubTask	Parent Task	Start date	End date	Resource assignment	Object assignment
S1	T1	21/09/2015	23/09/2015	R1,R2	O1
S2	T1	24/09/205	27/09/2015	R2,R3	O1
S3	T1	28/09/2015	30/09/2015	R1,R2	O1
S4	T2	22/09/2015	25/09/2015	R4	O2
S5	T2	26/09/2015	30/09/2015	R1,R4	O2
S6	T2	29/09/2015	03/10/2015	R2,R3	O2

6. Results and Discussion

The results after validating the inputs into the prototype are shown in Table 2. There were no violations for subtasks S1, S2 and S4. However, there were disjunctive constraint violation for S3.Also, disjunctive and precedence constraint violations for S5 and S6. The resource R1 assigned to S3 was already used by S5 which resulted in a disjunctive constraint as the resource cannot be shared between two activities at the same time. Similarly, Resource R2 assigned to S6 were used by S3 at the same time. Also, their precedence constraint applied to S5 and S6 stated S6 to start after S5 which was violated as S6 started before S5 ended. Therefore, the constraint violation framework could identify all the violations.

Table 2: Results after constraint validation

Subtask	Result
S1	No violation
S2	No Violation
S3	Disjunctive constraint violation
S4	No violation
S5	Disjunctive constraint violation, precedence violation
S6	Disjunctive constraint violation, precedence violation

Although this is an expected result and it could be solved without using any framework, the complexity of the problem increases with increase in the number of simultaneous activities, making it difficult to solve it without the help of a tool. In addition, the constraints are dynamic. Hence while adding an extra constraint, there is no need to hardcode the constraints again or alter the data graph. Only the shapes graph will be modified. The validation applies to current (which might have not violated any constraints previously) and future data. Isolating the data from the constraints makes it possible for keeping the constraints dynamic as the shapes graph can be modified at any stage without modifying the data graph and vice versa. Whenever, variables in a data graph changes, for example a process gets delayed or a resource is broken down, the remaining processes in data graph is evaluated against the modelled constraints to see what activities are affected and how they are affected. Keeping data graph and constraints separate also supports the implementation machine learning algorithms such as reinforcement learning where the agent and environment are different. Similarly, here constraint solver could act as an environment and provide rewards for actions taken by agent based on the no of constraint violations. These tools help to reschedule the processes and aid decision making during disruptions as the current state of work and the constraints are codified. It also acts as a 'unit testing' for the short term schedule data and supports collaboration, as it checks the data every time an edit is made with knowledge codified as constraints.

This problem also demonstrates the ability of linked data to traverse across the web of data. The disjunctive constraint was applied to the resources which don't have any schedule data associated with it. The schedule data was coded into the subtask as shown in Figure 4. However, the SHACL query could crawl through the data to identify the relevant time data from the resource assignments and making logical inferences on whether there were multiple assignments during the same time period. This shows the ability of linked data approaches to make semantic queries by traversing through the data. As the ontology layer is separate from the processing layer, queries need not have the know-how of the whole schema but only the attributes necessary for making the traversal.

The designed prototype can be used to look ahead meetings just like any 4D planning tool. The details about the relationship between the subtasks and resources, resources and constraints, constraints and subtasks, and subtasks and subtasks can easily be codified into a machine-readable format using the framework. The codified knowledge on the relationships and constraints can be reused further. This reduces the need for data input after a stage of saturation as the shapes graph gets populated during every session. The codified constraints in shape graph could be used for further session. For example, once a disjunctive constraint is assigned to a resource, whenever that resource is used, the constraint is automatically applied to it. Therefore, this framework helps to codify the constraint and relationships between resources, subtasks and tasks and this codified data can support decision making in the future. Indirectly, the knowledge concerning resources and task gets captured and codified within the system.

7. Summary and Conclusions

This paper presented a dynamic constraint solving framework to support look-ahead-planning in construction based on linked data. A prototype was developed based on the framework to test the efficacy of the framework. The prototype was developed based on 4D planning tool so that it gets integrated into the workflow. The developed prototype was able to identify the constraint violations within the detailed schedule data. This demonstrates the potential of the frameworks to be used to look ahead planning meetings to assist in decision-making process.

The current method using linked data enables the use of semantic queries to understand the constraint violations by traversing across datasets without the complete knowledge of the dataset's underlying schema. The framework enables domain knowledge generated and used during the look-ahead planning to be captured and codified so that it can be reused down the lane. This enables the experts to feed into the information during a meeting and then the system reuses the knowledge hence forth, without having to bring the expert again during disruptions. In addition, isolating the data modelling and constraint modelling to two different parts helps to enable dynamic constraint processing which is a necessary requirement for look ahead planning as the data inputs and constraints might change independently based on the dynamic nature of a construction site, however the data has to be validated and checked against the modelled constraints. The constraints modelled in SHACL acts similar to unit testing (in software testing) for the scheduling. Every time a change is made in the process information in the data graph, it is checked against the modelled constraints. In addition, separating constraint solving into a different graph supports the introduction of machine learning techniques such as reinforcement learning to automate look ahead planning, paving way for agile construction management practices as mentioned in Levitt (2011) to make decisions on the go based on inputs from various sources.

This paper has presented and demonstrated the framework for dynamic constraint solving using linked data. However, the testing has been done using a public construction dataset as a proof of concept. There is a need to test this framework in actual look ahead planning meetings to demonstrate the effectiveness and understanding the limitations. Also, future research should focus on an intuitive visual interface to generate the complex constraints so that it can be easily used by practitioners. In addition, there is an opportunity for learning from the codified constraint information, given the tasks and resources to predict the construction methods and generate schedules, which needs to be explored.

Acknowledgements

The PhD research of the author is co-funded by Bentley systems UK and, through a Skempton Scholarship, the Department of Civil and Environmental Engineering, Imperial College London. During the development of this paper, author was supported by the PhD enrichment scholarship from The Alan Turing Institute. The author acknowledges the supervisory inputs offered by Prof Jennifer Whyte and Dr David Birch and Dean Bowman. Also, author acknowledges the guidance offered by Prof. Jakob Beetz.

References

Alsafouri, S., & Ayer, S. K. (2018). Review of ICT Implementations for Facilitating Information Flow between Virtual Models and Construction Project Sites. Automation in Construction, 86, 176–189. https://doi.org/10.1016/J.AUTCON.2017.10.005

Anumba, C. J., Bouchlaghem, N. M., Whyte, J., & Duke, A. (2000). Perspectives on an integrated construction project modeL. International Journal of Cooperative Information Systems, 09(03), 283–313. https://doi.org/10.1142/S0218843000000107

Beetz, J., Van Leeuwen, J., & De Vries, B. (2009). IfcOWL: A case of transforming EXPRESS schemas into ontologies. Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM, 23(1), 89–101. https://doi.org/10.1017/S0890060409000122

Berners-Lee, T. (2006a). Linked Data - Design Issues. Retrieved January 14, 2019, from https://www.w3.org/DesignIssues/LinkedData.html

Berners-Lee, T. (2006b). Linked Data - Design Issues. Retrieved from https://www.w3.org/DesignIssues/LinkedData.html

Bilal, M., Oyedele, L. O., Qadir, J., Munir, K., Ajayi, S. O., Akinade, O. O., … Pasha, M. (2016). Big Data in the construction industry: A review of present status, opportunities, and future trends. Advanced Engineering Informatics, 30(3), 500–521. https://doi.org/10.1016/j.aei.2016.07.001

Bizer, C., Heath, T., & Berners-Lee, T. (2009). Linked Data - The Story So Far. International Journal on Semantic Web and Information Systems, 5(3), 1–22. https://doi.org/10.4018/jswis.2009081901

Eisenhardt, K. M., & Graebner, M. E. (2007). Theory Building from Cases: Opportunities and Challenges. Academy of Management Journal, 50(1), 25–32. https://doi.org/10.5465/AMJ.2007.24160888

Ekaputra, F. J., & Xiashuo Lin. (2016). SHACL4P: SHACL constraints validation within Protégé ontology editor. 2016 International Conference on Data and Software Engineering (ICoDSE), 1–6. https://doi.org/10.1109/ICODSE.2016.7936162

Giretti, A., Carbonari, A., Novembri, G., & Robuffo, F. (2012). Estimation of job-site work progress through on-site monitoring. 2012 Proceedings of the 29th International Symposium of Automation and Robotics in Construction, ISARC 2012, 11. https://doi.org/10.4017/gt.2012.11.02.348.704

Han, K. K., & Golparvar-Fard, M. (2017). Potential of big visual data and building information modeling for construction performance analytics: An exploratory study. Automation in Construction, 73, 184–198. https://doi.org/10.1016/j.autcon.2016.11.004

Hartmann, T. (2008). A grassroots model of decision support system implications by construction project teams. Stanford University, California, USA.

Huhnt, W., Richter, S., Wallner, S., Habashi, T., & Krämer, T. (2010). Data management for animation of construction processes. Advanced Engineering Informatics, 24(4), 404–416. https://doi.org/10.1016/j.aei.2010.07.009

Kim, K., Kim, H., Kim, W., Kim, C., Kim, J., & Yu, J. (2018). Integration of ifc objects and facility management work information using Semantic Web. Automation in Construction, 87, 173–187. https://doi.org/10.1016/J.AUTCON.2017.12.019

Knublauch, H., Allemang, D., & Steyskal, S. (2017). SHACL Advanced Features.

Levitt, R. E. (2011). Towards project management 2.0. Engineering Project Organization Journal, 1(3), 197–210. https://doi.org/10.1080/21573727.2011.609558

Liu, H., Lu, M., & Al-Hussein, M. (2016). Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry. Advanced Engineering Informatics, 30(2), 190–207. https://doi.org/10.1016/j.aei.2016.03.001

Morkos, R. (2014). Operational efficiency frontier: Visualizing, manipulating, and navigating the construction scheduling state space with precedence, discrete, and disjunctive constraints. Stanford University.

Pauwels, P., De Meyer, R., Van Campenhout, J., Meyer, R. De, & Campenhout, J. Van. (2010). Interoperability for the Design and Construction Industry through Semantic Web Technology. In: Declerck T., Granitzer M., Grzegorzek M., Romanelli M., Rüger S., Sintek M. (eds) Semantic Multimedia. SAMT 2010. Lecture Notes in Computer Science, vol 6725. Springer, Berlin, Heidelberg.

Pauwels, P., McGlinn, K., Törmä, S., & Beetz, J. (2018). Linked Data. In Building Information Modeling (pp. 181–197). https://doi.org/10.1007/978-3-319-92862-3_10

Pauwels, P., Zhang, S., & Lee, Y.-C. (2017). Semantic web technologies in AEC industry: A literature overview. Automation in Construction, 73, 145–165. https://doi.org/10.1016/J.AUTCON.2016.10.003

Soman, R. K. (2019). Modelling construction scheduling constraints using shapes constraint language (SHACL). *2019 European Conference on Computing in Construction (EC3)*. Chania, Greece.

Subramanian, P. S., Songer, A. D., & Diekmann, J. E. (2000). Visualizing Process Performance. Computing in Civil and Building Engineering (2000), 1–6. https://doi.org/10.1061/40513(279)1

Terkaj, W., Schneider, G. F., & Pauwels, P. (2017). Reusing Domain Ontologies in Linked Building Data : the Case of Building Automation and Control. *Proceedings of the 8th Workshop Formal Ontologies Meet Industry, Joint Ontology Workshops* 2017, CEUR Workshop Proceedings, (p2050).

Waterhouse, R., Kemp, A., Matthews, A., Moulds, A., Mordue, S., Malleson, A., & Philp, D. (2016). National BIM Report. In National BIM Library.

Whyte, J., & Levitt, R. (2011). Information Management and the Management of Projects. In The Oxford Handbook of Project Management. https://doi.org/10.1093/oxfordhb/9780199563142.003.0016

Whyte, J., Stasis, A., & Lindkvist, C. (2016). Managing change in the delivery of complex projects: Configuration management, asset information and “big data.” International Journal of Project Management, 34(2), 339–351. https://doi.org/10.1016/j.ijproman.2015.02.006

Zhang, C., & Beetz, J. (2016). Querying Linked Building Data Using SPARQL with Functional Extensions Querying Linked Building Data Using SPARQL with Functional Extensions. Ecppm2016, (October).

Situation Awareness and Sensing Technologies

Use cases for the Internet of Things (IoT) in the construction sector: Lessons from leading industries

Arka Ghosh[1], M. Reza Hosseini[1], David Edwards[2], Mohamad Kassem[3, *], Monica Matteo-Garcia[2]

[1]School of Architecture and Built Environment, Deakin University, Geelong, Australia
[2]School of Engineering and Built Environment, Birmingham City University, Birmingham, United Kingdom
[3]Department of Mechanical and Construction Engineering, Northumbria University, Northumbria, United Kingdom
[2]School of Engineering and Built Environment, Birmingham City University, Birmingham, United Kingdom
[*]email: mohamad.kassem@northumbria.ac

Abstract

This study conducts a cross-sectoral comparative analysis of academic and industry literature to determine the use cases of the internet of things (IoT). Specifically, the research seeks to explore digital applications (e.g., building information modeling (BIM), radio frequency identification (RFID)) within the construction supply chain – a sector berated for its lack of innovation. An interpretivist epistemological lens provides the overarching methodological approach adopted in which the literature constitutes units of analysis. Ensuing discussion defines the architecture of proposed real-life scenarios and provides a description of an IoT layout for these scenarios. In practical terms, the study contributes to the field by raising awareness of potential use cases of IoT for construction practitioners as 'proof of concepts'. For researchers, the findings provide a blueprint template layout of suggested use cases to be tested in future research studies hence, offering a sound basis and a fertile ground for advancing the body of knowledge on this topic area.

Keywords: IoT, Industry 4.0, Industrial Internet, BIM, RFID

1. Introduction

Customers have heightened, new, and customized expectations today by learning from other industries and demand that the construction industry brings similar innovations. A case in point being hybrid renewable energy solutions linked to a building's daily carbon footprint (Woodhead *et al.* 2018). Device-agnostic mobile applications are the need of the hour that shall identify crucial and critical information and cater to the needs of consultants, contractors, and clients in an integrated manner. Researchers conclude that apart from design intent and clarification, there are slight differences in the information demands of consultants and contractors; however, client’s needs deviate significantly from them (Nourbakhsh *et al.* 2012).

The ease of accessing data on sites is of primary concern while developing smart tools and data visualization platforms. Strategies like developing BIM-enabled tools to allow site workers using portable devices to access design information and to capture work quality and progress data on-site are the need of the hour (Davies and Harty, 2013). Knowing that the various sectors where wearable technologies have been greatly applied are not a high-risk industrial sector like construction, there is an urgent need to change the status quo in terms of the application of wearable technologies in construction. (Awolusi *et al.* 2018). Today there is an urgent need to raise awareness and communicate the success of innovative digital technologies and solutions to revolutionize the construction industry.

The Construction Industry has often been seen as laggards when it comes to adapting to emerging technologies. The Internet of Things (IoT) provides exciting opportunities for the Construction Industry to shed this unwanted tag and be on the forefront of utilizing IoT to solve its time and resource constraints and frequent defaults. Construction operations are typically spread across large areas and require remote collaboration between multiple contrasting departments and resources that create the need for ubiquitous, rapid, and automated decision-making on the worksite (Louis & Dunston 2018). The Internet of Things (IoT) utilizes systems such as sensors and connected devices to monitor real-time parameters and harness the information gleaned through techniques like data analytics and data mining to provide visually informative end-results. For the construction industry to address the current technological challenges in this Industry 4.0 age, it needs to adapt and transform itself from its traditional primitive methods to digitalised automated systems which will act as a major step forward towards improving its productivity, efficiency, and sustainability and lead to dynamic planning and management (Dallasega 2018).

2. Research Methodology

This paper follows an open-ended research literature review of scientific publications obtained from Scopus and Web of Science databases. The search query included "internet of things” OR “industry 4.0” OR “digital engineering” OR “big data" OR "operational technology" OR "digital" OR "cyber-physical systems" OR "digitalisation" OR "industrial internet" OR "industrial internet of things" AND "construction industry". Publications are selected with a focus on relevant practical used cases in the construction sector and provides relevant “proof of concepts” of practical implementation of Internet-of-Things to facilitate its uptake in the construction industry. Review papers and conceptual frameworks were avoided, and only real-life case studies were included, which resulted in 21 publications included in the scope of this study.

3. Use Cases

Publications are selected with a focus on relevant practical used cases in the construction sector and provides relevant “proof of concepts” of practical implementation of Internet-of-Things to facilitate its uptake in the construction industry. Fig.1 shows the plethora of opportunities and use cases that have been focused upon in this study and provide a description of relevant used cases in these categories from literature.

Figure 1: Sub-domains of IoT adoption in the construction industry

3.1 Raising awareness and communicating the success RFID

Despite its enormous potential, RFID is adopted at a leisurely pace in the construction industry. There are two possible ways to achieve its broader applications. One is to inform the industry of the potential in an effective way. The scenarios identified in this work, animated later using Google Sketch Up, can serve as a vehicle for better communicating the potential of RFID to construction practitioners (Lu, Huang, and Li, 2011). Wang (2014) fused RFID in prefabricated construction to improve construction productivity. Kereri and Adamtey (2019) investigated key drivers and success factors for RFID adoption in the residential or commercial construction industry. Lanko *et al.* (2018) considered the application feasibility of blockchain in logistics of construction materials through the usage of RFID technology. Xue *et al.* (2018) provided practitioners with guidelines for linking RFID to BIM for various construction engineering and management needs.

3.2 Safety monitoring

Construction worker safety is of paramount importance towards attaining a successful zero-casualty objective targeted by most project managers. There is a need to develop a holistic and collaborative information integration framework for safety monitoring that collects, analyzes, and disseminates safety information (Xu, Chong and Liao, 2019). In response to this need, researchers have developed innovative strategies to improve, enhance, and integrate worker safety, especially in the construction of tall buildings. Fang (2019) developed an automated inspection method to check PPEs' usage by steeplejacks who are ready for aerial work beside exterior walls. RFID-based location and tracking technology, centimeter-level of ultrasonic detection technology, and infrared access technology were developed in three-tier network architecture to help workers change their risky behaviors and avoid accidents on the changing construction site (Zhou and Ding, 2017). The adoption of wearable technology has the potential for a result-oriented data collection and analysis approach providing real-time information to construction personnel taking valuable lessons from other industrial sectors (like mining and manufacturing) to measure and monitor a wide variety of safety performance metrics in construction (Awolusi, Marks and Hallowell, 2018). Edirisinghe (2018) envisaged that the future construction worker who is part of the digital skin of the context-aware future construction site would wear smart wearables. These include e-textiles, such as smart safety vests (Edirisinghe and

Blismas, 2015), smart hardhats (SmartCap, 2017).

3.3 Data Visualization

The success of incorporated IoT techniques will significantly depend on the ease with which critical data is displayed, and key performance indicators and metrics captured and reported in-time. Real-time representation dashboards such as Google Data Studio will allow the graphical presentation of the data to be improved and offer a more user-friendly tool (Martín-Garín *et al.* 2018). Wireless sensor technology can be used by engineers to monitor conditions in and around buildings. An interface to review the data and a web-based system was developed that allows a user to mine the database using parameters such as the type of data, location of the sensor, and the time of data acquisition (Jang, Healy and Skibniewski, 2008). Edmondson (2018) harnessed the capacity to visualise and predict flood performance to anticipate surcharging of manholes and inlets as well as discharge events from combined sewer overflows (CSO) to develop a Smart Sewer Asset Information Model (SSAIM) for an existing sewerage network opportunity within the wastewater sector to harness and report in real-time sewer condition data for operation management.

3.4 Structural Engineering Applications

The Internet of Things has essential applications in the field of structural engineering. Naser (2019) developed foldable structural components (called Autonomous Structural Reconfiguration (ASR)) and incorporated them with artificial intelligence and Internet of Things (IoT) technologies. Integrated into structural engineering applications, this institutes the first step towards realizing autonomous and resilient infrastructures. These components act as secondary, and independent structural systems, that allow civil construction to autonomously reconfigure their internal structure to adapt to severe loading conditions in real-time. Zhang *et al.* (2018) analyzed the practical application value of the IoT technology in the crack identification of bridge structures and established a bridge structural health monitoring system based on IoT technology.

3.5 Prefabricated Construction

The Internet-of-Things can act provide a much-needed boost to prefabricated and modular construction. Zhong (2017) provides evidence how the Hong Kong Housing Authority (HKHA) sped up housing delivery by employing advanced technologies, including Building Information Modelling (BIM) and Radio Frequency Identification (RFID), in some of their pilot prefabrication-based construction projects. Tao *et al.* (2018) developed an IoT-based framework to monitor the greenhouse gas (GHG) emissions in real-time for manufacturing prefabricated components.

3.6 Cloud-based platform

Data stored as cloud asset could sense its real-time status, adapt to different working scenarios, be controlled remotely, and shared among agencies. It enables accurate real-time control of every asset, and thus improves the management efficiency and effectiveness (Xu, *et al.* 2015; Xu, *et al.* 2018). Núñez *et al.* (2018) developed a mobile computing-based knowledge management platform to manage lessons learned in different Chilean construction projects of small and medium enterprises through an iterative and user-centric methodology.

3.7 Construction waste management

The Internet-of-Things can act as an effective means to monitor and reduce construction waste. Chen (2002) developed a group-based incentive reward program (IRP) to encourage workers to minimize avoidable wastes of construction materials by rewarding them according to the amounts and values of materials they saved. The bar-code technique is used to facilitate effective management of construction materials. An IRP-integrated construction management system is also introduced to avoid jerrybuilding and solve the rescheduling problem due to rework of quality failure.

3.7 Educational opportunity

The growing emergence of IoT provides excellent opportunities for active participation of researchers and students to develop innovative solutions and use cases for applicability in real-life scenarios in the construction sector (Dave *et al.* 2018). Nati *et al.* (2013) demonstrated that university campuses were the perfect testbed for experimenting with the Internet of Things incorporating the involvement of real users and satisfying the need for emerging realism in research work.

4. Barriers to IoT Adoption in the construction industry

Some of the possible barriers identified and measures to mitigate them regarding IoT adoption in the construction industry are as follows:

a.) **Incompatibility and unclear value propositions:** Consistent coordination between various departments regarding the collection, monitoring and regulation of data along with their processing and analysis at an integrated level to enhance decision-making and definite value addition is a challenge and significant hindrance for smooth IoT adoption. This obscurity can only be resolved through proper integrated planning before employing IoT devices or techniques on the field. Clear guidelines, policies, and benchmarking regarding the use of IoT devices and procedures would greatly assist in defining clear procedures and policies.

b.) **Data privacy and security**: The explosion of enormous data generated by IoT devices lead to concerns over its legality, privacy, and governance. Misuse could prove to be immensely counterproductive to the main aims of employing IoT. Unscrupulous hackers and data thieves may maliciously corrupt stored data or use historically compiled data to further their nefarious purposes. The security protocols and access have to be carefully developed and monitored to prevent this occurrence.

c.) **Bureaucratic governance structures:** Construction industry has traditionally been governed by rigid and bureaucratic hierarchies which are resistant to change and evolution. This provides a significant hindrance to the gradual and smooth uptake of IoT techniques and processes. The only solution is to convince the important decision-makers of the numerous benefits of IoT especially in a financial context so that change is effected from a top-down flow making it more effective and integrated, rather than a bottom-up approach which results typically in point-solutions as observed from the literature review.

d.) **Business planning and models:** Effective business plans are to be formulated incorporating the IoT techniques. A practical benefit-cost analysis proves necessary evidence before the uptake of any new technique in a project. Failure to plan the absorption in a systematic process would provide to be a significant hindrance for the successful adoption of IoT in construction projects.

5. Limitations and Future Scope

This study provides a preliminary exploration of the various possibilities and potential of the applicability of Internet-of-Things in the construction sector to satisfy the heightened demands of customers in the present technological age. Since the Internet of Things is a nascent field of study concerning the construction industry, only 21 publications referring to real-life case studies were included in this study. With growing interest in this field of research, it is highly possible to have additional case studies highlighting applicability and effectiveness of Internet-of-Things in the construction sector which would increase the body of knowledge that we currently hold in digital construction techniques and tools. The findings provide a blueprint template layout of suggested use cases to be tested in future research studies; hence, offering a sound basis and a fertile ground for advancing the body of knowledge on this topic area.

6. Conclusion

Internet-of-things can significantly enhance and automate the decision-making process in construction projects. While it can be argued that the practice of daily meetings for a project comprises monitoring and control for decision-making, its low temporal frequency is detrimental to project performance in terms of taking timely actions based on up-to-date information from the field (Louis and Dunston, 2018). Project delivery times and quality can be upgraded by utilizing the principles and techniques of IoT.

It was observed from the preliminary literature review that most of the solutions were point solutions that aimed to satisfy short-term localized goals instead of developing an integrative system for providing "umbrella solutions" targeting any significant aspect of the construction industry as a whole. Although many review papers tried to highlight the possible future impact of growing digitization and IoT in the construction sector, a bibliographic approach without relevant human or industry perception through questionnaires was observed. Various techniques like big data management, data mining, cyber-physical systems, and proposed conceptual frameworks were discussed without sufficient successful examples from real-life case-study implementation. There is an urgent need to translate the theory of IoT into practice in the construction industry with an integrated ecosystem changing with a view towards possible hindrances and measures to mitigate them chalked out in advance.

References

Awolusi, I., Marks, E. and Hallowell, M. (2018). Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices. *Automation in Construction*, 85, pp.96-106.

Awolusi, I., Marks, E. and Hallowell, M. (2018). Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices. Automation in Construction, 85, pp.96-106.

Chae, M., Yoo, H., Kim, J. and Cho, M. (2012). Development of a wireless sensor network system for suspension bridge health monitoring. Automation in Construction, 21, pp.237-252.

Chen, Z., Li, H. and Wong, C. (2002). An application of bar-code system for reducing construction wastes. Automation in Construction, 11(5), pp.521-533.

Dallasega, P., (2018), 'Industry 4.0 Fostering Construction Supply Chain Management: Lessons Learned From Engineer-to-Order Suppliers', IEEE Engineering Management Review, 46 (3), pp. 49-55.

Dave, B., Buda, A., Nurminen, A. and Främling, K. (2018). A framework for integrating BIM and IoT through open standards. Automation in Construction, 95, pp.35-45.

Davies, R. and Harty, C. (2013). Implementing 'Site BIM': A case study of ICT innovation on a large hospital project. Automation in Construction, 30, pp.15-24.

Edirisinghe, R. (2018). Digital skin of the construction site. Engineering, Construction and Architectural Management.

Edmondson, V., Cerny, M., Lim, M., Gledson, B., Lockley, S. and Woodward, J. (2018). A smart sewer asset information model to enable an 'Internet of Things' for operational wastewater management. Automation in Construction, 91, pp.193-205.

Fang, Q., Li, H., Luo, X., Ding, L., Luo, H. and Li, C. (2018). Computer vision aided inspection on falling prevention measures for steeplejacks in an aerial environment. Automation in Construction, 93, pp.148-164.

Jang, W., Healy, W. and Skibniewski, M. (2008). Wireless sensor networks as part of a web-based building environmental monitoring system. Automation in Construction, 17(6), pp.729-736.

Kereri, J. O., & Adamtey, S. (2019). RFID use in residential/commercial construction industry. Journal of Engineering, Design and Technology.

Lanko, A., Vatin, N., & Kaklauskas, A. (2018). Application of RFID combined with blockchain technology in logistics of construction materials. In MATEC Web of Conferences (Vol. 170, p. 03032). EDP Sciences.

Louis, J. and Dunston, P. (2018). Integrating IoT into operational workflows for real-time and automated decision-making in repetitive construction operations. Automation in Construction, 94, pp.317-327.

Lu, W., Huang, G. and Li, H. (2011). Scenarios for applying RFID technology in construction project management. Automation in Construction, 20(2), pp.101-106.

Martín-Garín, A., Millán-García, J., Baïri, A., Millán-Medel, J. and Sala-Lizarraga, J. (2018). Environmental monitoring system based on an Open Source Platform and the Internet of Things for a building energy retrofit. Automation in Construction, 87, pp.201-214.

Naser, M. (2019). Autonomous and resilient infrastructure with cognitive and self-deployable load-bearing structural components. Automation in Construction, 99, pp.59-67.

Nati, M., Gluhak, A., Abangar, H., & Headley, W. (2013, June). Smartcampus: A user-centric testbed for internet of things experimentation. In 2013 16th International Symposium on Wireless Personal Multimedia Communications (WPMC)(pp. 1-6). IEEE.

Núñez, D., Ferrada, X., Neyem, A., Serpell, A., & Sepúlveda, M. (2018). A user-centered mobile cloud computing platform for improving knowledge management in small-to-medium enterprises in the Chilean construction industry. Applied Sciences, 8(4), 516.

Nourbakhsh, M., Mohamad Zin, R., Irizarry, J., Zolfagharian, S. and Gheisari, M. (2012). Mobile application prototype for on-site information management in construction industry. Engineering, Construction and Architectural Management, 19(5), pp.474-494.

Tao, X., Mao, C., Xie, F., Liu, G., & Xu, P. (2018). Greenhouse gas emission monitoring system for manufacturing prefabricated components. Automation in Construction, 93, 361-374.

Wang, J. (2014). Based on RFID prefabricated building component design and monitoring system research. Advanced Materials Research, 983, pp. 359-362. Trans Tech Publications.

Woodhead, R., Stephenson, P. and Morrey, D. (2018). Digital construction: From point solutions to IoT ecosystem. Automation in Construction, 93, pp.35-46.

Xu, G., Huang, G. and Fang, J. (2015). Cloud asset for urban flood control. Advanced Engineering Informatics, 29(3), pp.355-365.

Xu, G., Li, M., Chen, C. and Wei, Y. (2018). Cloud asset-enabled integrated IoT platform for lean prefabricated construction. Automation in Construction, 93, pp.123-134.

Xue, F., Chen, K., Lu, W., Niu, Y., & Huang, G. Q. (2018). Linking radio-frequency identification to Building Information Modeling: Status quo, development trajectory and guidelines for practitioners. Automation in Construction, 93, 241-251.

Zhang, L., Zhou, G., Han, Y., Lin, H., & Wu, Y. (2018). Application of Internet of Things Technology and Convolutional Neural Network Model in Bridge Crack Detection. IEEE Access, 6, 39442-39451.

Zhong, R., Peng, Y., Xue, F., Fang, J., Zou, W., Luo, H., Thomas Ng, S., Lu, W., Shen, G. and Huang, G. (2017). Prefabricated construction enabled by the Internet-of-Things. Automation in Construction, 76, pp.59-70.

Zhou, C. and Ding, L. (2017). Safety barrier warning system for underground construction sites using Internet-of-Things technologies. Automation in Construction, 83, pp.372-389.

Sensing technologies embedding construction workers outcomes/key performance indicators

Diego Calvetti[1, *], Miguel Chichorro Gonçalves[1], Pedro Nuno Mêda Magalhães[1], and Hipólito José Campos de Sousa[1],
[1]CONSTRUCT-Gequaltec, Porto University Faculty of Engineering, Porto, Portugal.
[*] email: diego.calvetti@prodyoup.com

Abstract

Construction Industry is and will continue to be crucial for countries' economies. The successful implementation of innovations on the context of the Industry 4.0 demands efforts in technology, processes, and people. The manufacturing industry increases its productivity faster than construction. Labour processes in the manufacturing industry are directly connected to machines. On the other hand, in construction tasks, the workers are the principal dimension of labour productivity, namely during the construction and use stages. The motivation links with the awareness that is necessary to find a balance between technology, people and processes in order to find the best roadmap towards the introduction of innovations, goals achievement and obtain added value from the implementation processes. From this, the workers performance management and potential from the application of sensing technologies to collect data during construction projects was emphasized.

To get the required data, an integrated model must be set aligning construction tasks, sensing technologies for data collection, key performance indicators related to workforce and main constraints in project management. This proposed model must be combined with building information modelling to achieve higher outcomes. The result is the assessment of construction projects performance based in the human resource integration with the current information systems and the new sensing technologies.

The main deliverable is a framework composed by different parts as follows: - basic elements of the construction tasks; equipment, products, workers;

- five major types of sensing technologies;
- twelve KPI's connected to workers in construction;
- seven main construction project management constraints;

Higher industry productivity implies workers monitoring and the identification of ways to improve their performance. Monitoring produces data with big potential for other processes, many of them within the BIM that presently rely on manual processes. From the top project management and governance point of view, this information constitutes relevant data towards smart contracts requirements and assumptions. The role of the worker as builder and as manager of information constitutes the main challenge.

Key words: Construction 4.0, Project management, Productivity, BIM, Smart contracts, Workers, Sensing technologies

1. Introduction

The Construction Industry is essential for the countries' economies and impacts in several dimensions. Multiple global megatrends are shaping the future of construction. These fit on market and customers' requirements, sustainability and resilience targets, political and regulatory aspects and society and workforce role (Forum, 2016). The use/adoption of technology/digitalization is assumed as an "enabler" towards these megatrends. It is found that through technology it will be possible to shape the pace of construction in a route to higher productivity levels (McKinsey, 2017). To measure productivity in construction it will always be necessary to measure fundamental aspects, as the construction products, the equipment's and the human resources. These three dimensions are the base for the materialization of a construction outcome or construction entity that can be further evaluated in terms of cost, time, quality, safety, and environment, among others.

The implementation of innovations in construction on the context of the Industry 4.0 implies Technology, Processes and People (CIB Publication: 373, 2013; Sousa and Magalhães, 2017). The identification of the best technology for each or a group of processes, the refurbishment of these processes towards technology and the identification of the roles, training needs and involvement of the persons/construction agents seems quite an easy equation, but lacks in terms of balance in most strategies of innovation and implementation.

All the above mentioned and the awareness that human resources play an essential role not only for the implementation of innovations but also as a field for the implementation of these innovations, constitute the starting point of the present research. Figure 1 frames on one side the main "traditional" requirements of the construction industry (aspects that constitute a scope for performance measurement) and on the other side the main technological drivers towards the Industry 4.0 vision.

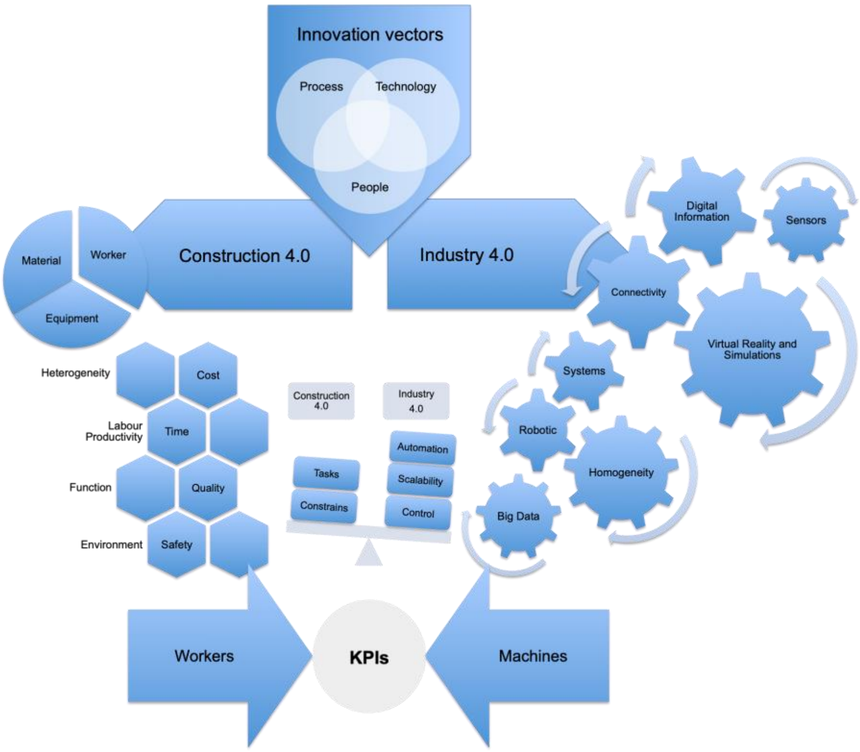


Figure 1: 4.0 approaches to collect KPIs

The effective assessment of productivity in construction is an imperative to improve performance over time, cost and quality. The current technological advances allow the implementation of new electronic performance monitoring processes on workers in the construction industry. Systematic control of constructive operations streamlines specific aspects of the activities under development, highlighting the information requirements for decision-making within an agile management environment (Yang *et al.*, 2015).

2. The assessment of the productive performance of workers

2.1 Initials considerations

Corporations seeking to increase their profits are naturally interested in autonomously monitoring services and workers (Alder, 2001). The ways for implementing operational control methods vary significantly within the framework of construction companies. Work activities involve multiple stakeholders and thousands of physical elements; managing these activities to achieve maximum operational efficiency is extremely complex (Yang *et al.*, 2015). Within a corporate and strategic vision, productivity management should include: the performance of measurement; qualitative and quantitative assessment; and the implementation of actions to control and improve processes (Sink, 1985). The evaluation of the productive performance in the industry is usually based on the methodology of measurement and rationalization of the outputs that are the results of the processes, through the inputs needed to develop the work (Sink, 1985). Performing data collection manually by direct observations is time-consuming and costly, labor-intensive and highly prone to failures. Furthermore, data post-evaluation models are most successfully applied in companies in which the manufacturing process is routinely repeated. In the case of the construction industry, where projects have higher non-repeatability characteristics, post-data evaluation techniques will have limited benefits. (Yang *et al.*, 2015)

Mckinsey (2017) report points out that the use of technology in service fronts has a potential to increase from 14% to 15% the productivity index of the global construction industry. The electronic measurement of performance has the potential to identify the most relevant areas for applying innovation in service fronts and thus, to maximize the effectiveness of the use of other technologies in the works. Electronic devices for data collection in engineering works must meet many criteria: cost-benefit; strength and durability; easy use and training; appropriate dimensions; scalability; reliability; low rates of data transmission and storage; data security (Cheng *et al.*, 2012).

2.2 Construction tasks

It is through the physical and mental effort of direct labour that construction activities are performed. This effort can be replaced or attenuated through the use of equipment, machines or power tools. However, within the current reality of construction, even in activities with a high degree of mechanization the presence of a human operator is still necessary. In fact, human resource performance is the main productive factor in the traditional construction industry.

In general, the construction tasks are based on manual work system or worker-machine system without processes based on automated work sub-system. The manual tasks commonly require the use of hand tools (e.g., hammers, saws, trowel) (Groover, 2007) to apply the products. In addition, some equipment (e.g., crane, backhoe, road roller) or portable power tools (e.g., drills, circular saw, routing tools) are operated by human workers as construction aid. The construction products are (framed by function or form or material or any combination of these) intended to be used as a construction resource (ISO 12006-2, 2015). At the construction yards, rarely is seen automated or semi-automated machine processes performed without human assistance. As a result, the worker must be in physical contact with the tools, machines, and products in a specific geolocation on-site to perform the tasks (Navon and Goldschmidt, 2003). Within the service fronts of civil engineering works, mainly in refurbishment interventions, direct labor can be identified as the center of production. The Portuguese legal diploma addressing price revision regime for construction works, determines 40% for the workforce costs within new building construction and 53% for refurbishment operations (Decree-law, 2004). This underlines the added-value that can represent for the sector economy the improvement of workers performance.

2.3 Sensing technologies

When applying electronic devices to monitor tools and machines, it is necessary to look for elements of small dimensions and lightness, once workers will handle them. The same principle is relevant for the monitoring of products and especially when monitoring the workers themselves. In addition, considering that these elements are in great number in construction environments, the low cost per monitored element positively potentiates the application of this type of technology. It worth's mentioning that most of the technologies demands energy for its operation. The autonomy appropriate to the use, size and weight of the supply (encapsulated on the device) and ergonomics are main aspects to be balanced. However, when it is sought to monitor vehicles and equipment there is no need to require miniature devices, and given the reduced number of devices, higher unit costs can be accepted. In all cases the technology must have a wireless concept, it is desired that the device can be contained in a single enclosure and that does not require external elements such as wires or antennas.

Productivity monitoring in construction projects is highly complex, as it involves the evaluation of all elements (products, tools, equipment, workers, etc.) over time, within a context of several interactive processes. With this, different approaches were observed that seek to determine and improve performance in segments of the wide production process. For example, monitoring materials and application elements to assess the times they remain in stock/storage, handling and finally when they are built, constitute extremely relevant information in view of a Lean Construction concept. Moreover, locating and efficiently positioning these elements in real time leads to directly positive results in on-site productivity and enables integrated management of the project schedule and quality, as well as the computerization of the BIM model to obtain 3D/4D.

Most of the studies focus on identifying the areas of occupation and trajectories carried out by workers during their working day. Indeed, based on their occupation are diagnosed the time elapsed within areas considered as production or idle. Also, with the advent of small devices capable of measuring acceleration/speed and wearable technologies, an analysis of the movements and gestures of the workers can be provided. Where within a concept of skeletonization one can even diagnose direct work actions (e.g., hammering, sawing, painting) allowing a detailed modeling of the production processes. Figure 2(a) shows the Electronic Performance Monitoring concept where the workers must use the electronic devices (that have embedded software) during the workday, and these devices must have communication to deliver the data for the interface software. Figure 2(b) highlights the sensing technologies in electronic devices for the electronic monitoring of performance in construction works.

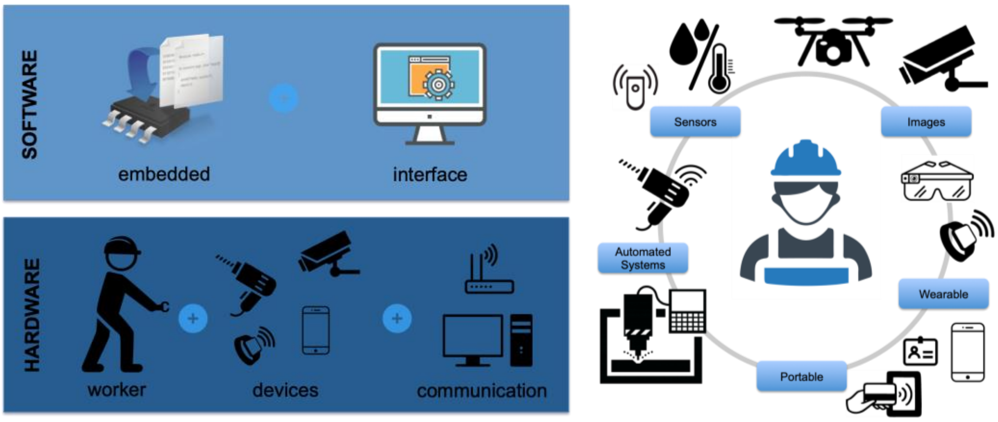


Figure 2:(a) Electronic Performance Monitoring conception, (b) Devices to collect data

Nonetheless, the current technological advances allow the automation of some manual data collection processes. As well, it allows the development of new ways of measuring the performance of workers. It can streamline current methods of checking and controlling access at locations through badges and readers and/or filming. Machinery and equipment used in construction tasks may inform their time of use and/or quantity of product applied. Also, external sensors can measure environmental conditions at service fronts, such as temperature and humidity. New analysis processes focus on the geographical mapping of the location and trajectory of the workers, in order to quantify the time spent in specific areas and in motion. Several studies look for the detailed analysis of the movements and gestures of the workers through the method of skeletonization.

2.4 Outcomes/key performance indicators

It is based on the analysis of historical data of the projects that are determined the Key Performance Indicators (KPI), and also, are classified the best benchmarking (Groover, 2007). In this context, project data on the tasks, inputs, time and human resources expended are analyzed. Depending on the process of each company, these records may be contained in physical documents, or already in digital format. The main process for obtaining this data in the field is through human appropriation. Still, it is through human observation that process modeling and time studies are performed. Directly related to the analysis of the performance of the workers and teams stand out the scientific models in the study of the time and in the measurement of the work done. (Adrian, 2004; Groover, 2007)

Following are presented 12 KPIs for standardization of performance metrics for construction workers based on data collected by electronic devices. To begin with the classic approach to measuring the productivity through the ratio of the input per output (Sink, 1985). Furthermore, the performance indicators classified as quantitative and qualitative (Cox, Issa and Ahrens, 2003). At the same time, the KPIs classified as objective measures and subjective measures (Chan and Chan, 2004). Also, some aspects of the work of Adrian (2004) and the safety accidents measure approach of ConocoPhillips corporation (Freibott, 2013) are connected to the presented KPIs .

Units per Man-Hours (input per output): The quantitative analysis of the Man-Hour spends in work to performer a unit task is the measure approach most applied in the construction industry. (Sink, 1985; Cox, Issa and Ahrens, 2003)

Value associated per Units (input per output): Another input per output quantitative method is related to the measure of the unit of complete work per the monetary value associated (e.g. Dollar and Euro). (Sink, 1985; Cox, Issa and Ahrens, 2003)

On-time completion and time variation: Based on the schedule of the construction project it identifies the finish estimated of the tasks. By measure, the completion of tasks and the achievement of milestones it is possible determines the schedule performance. It allows the on-time completion analysis and the overview of the time variation in the estimated project. (Cox, Issa and Ahrens, 2003; Chan and Chan, 2004)

Human resource management: The measurement of the HR spent in the construction projects is extremely important for assessment time and cost. It allows the determination of the Man-Hours expected against the Man-Hours real performed. (Sink, 1985; Cox, Issa and Ahrens, 2003)

Quality control and rework: The quality of a construction project is related to the scope specification and features. Quality failure account in 6% to 12% of the overall expenditure Man-Hours. The rework increase the Man-Hour needed and greatly increase the overall time and cost of the projects. (Cox, Issa and Ahrens, 2003; Chan and Chan, 2004)

Percent complete and speed of construction: The percent complete and speed of construction are the actual status of the project in determinate date. Consequently, is a partly of the on-time completion and time variation. It method is widely used in measuring the monthly performed, and allows a perception of the speed of the construction. (Cox, Issa and Ahrens, 2003; Chan and Chan, 2004)

Earned Man-Hours and values: The earned value and the earned Man-hours are connected to the completed work in place. It provides an indicator of job productivity based on the estimated Man-hours and values against that real performed. (Cox, Issa and Ahrens, 2003; Chan and Chan, 2004)

Lost time accounting and identification: The impact factors of unproductivity are response for lost of time in the construction tasks. It is extremely important identify each factor and measure their impact. Most important is assessment productivity to determine qualitatively and quantitatively what are the factors that cause the most impact, both in productive activities and in the events that generate workers' idleness, which will allow the development of effective actions to modify the behaviour of a productive process. (Cox, Issa and Ahrens, 2003; Adrian, 2004)

Punch list and Extra time: Usually, the punch list approach occurs at the end of any task, phase or project. The extra time required for the workforce is another specific situation that has to be analyzed. As a result, quantifying that amount of Man-Hours will allow the best understanding of resource spent during a construction project. (Cox, Issa and Ahrens, 2003)

Safety (accident and hazard rates): Nowadays safety should be a major concern in construction projects. The quantification of the work injures accidents started with the work A. W. Heinrich (1931), passing per Frank E. Bird Jr. (1969) to in 2003 a study by ConocoPhillips Marine. Based on the ConocoPhillips Model it is connected the number of unsafe actions on-site in the way to diagnosis the potential workers' recordable injuries, lost workdays and, death fatality. (Cox, Issa and Ahrens, 2003; Freibott, 2013)

Absenteeism: A worker out of service is a Man-Hour lost. The number of lost Man-Hours due to absenteeism over the duration of the construction project should be measured to provide historical data. (Cox, Issa and Ahrens, 2003)

Motivation: The understatement of the workers' motivation is very important to achieve productivity. At the same time, it is a complex and difficult assessment. A motivated worker will present the best attitude towards the tasks and the environment created on the job site. (Cox, Issa and Ahrens, 2003)

2.5 Main constraints in project management

Constraints are assumed as limiting factors that affect the execution/performance of a project or process. Project success (or part of it) should be measured based on pre-established terms of completing the project within the constraints of scope, time, cost, quality, resources and risk. It is the main role of the project manager to "manage" these constraints. (PMI, 2017)

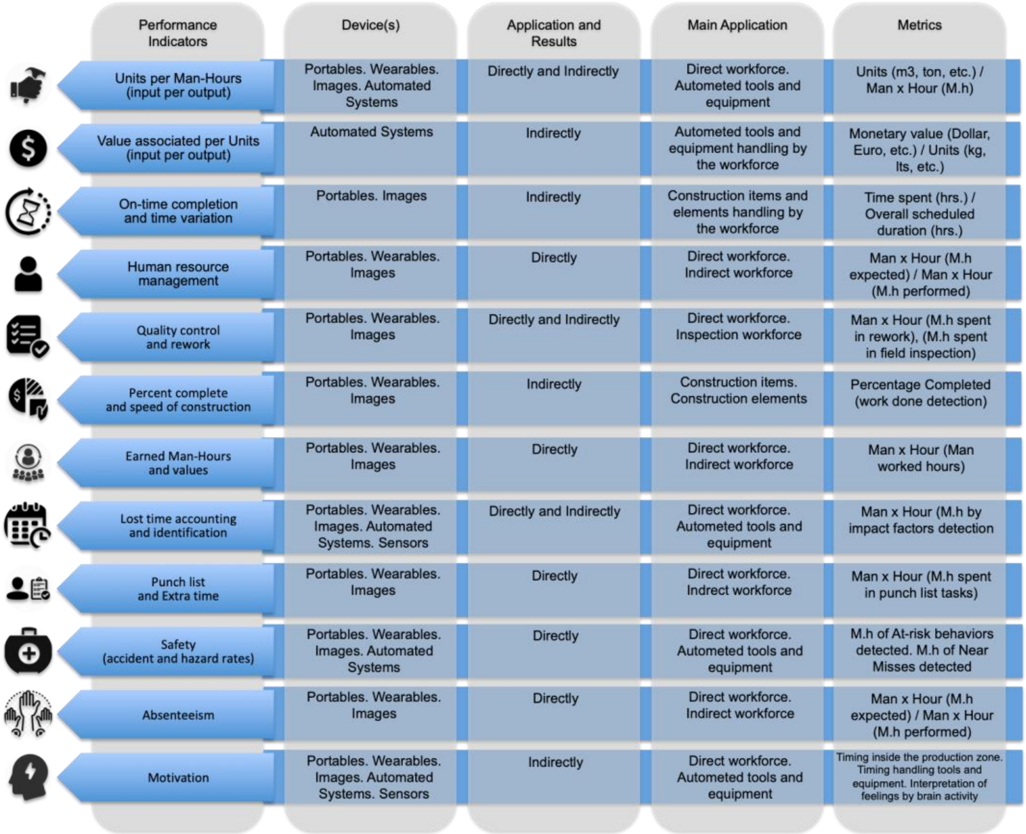
Besides these overall well-known constraints (Cost, Time, Quality and Scope/Function), construction projects are directly affected by others as safety, environment and labour productivity. Nowadays, it is mandatory in construction yards to increase the occupational safety and health performances. The International Organization for Standardization through ISO 45001:2018 established the requirements that should be implemented in projects (ISO 450001, 2018). Aspects related to climate change and environmental protection agreements have placed the environmental theme in evidence. As result, it can be considered as another dimension of performance assessment in engineering projects (Gangolells *et al.*, 2009). Finally, the labour productivity as a fundamental engine of the construction projects drives the relationship among these other factors, in order that any poor performance in labour productivity is likely to affect the others and/or cause constraints.

3. The framework for standardization of the KPIs

Based on the above explanation about the data collected by electronic devices and workers' performance in the context of the standards of metrics and benchmarking, Figure 3 presents the framework for standardization of the electronic performance metrics.

All the concept of collecting Man-hours is based on workers' personal identification, position, geolocation, trajectory, movements (gesture). In addition, the integration of information from automated tools and equipment also allows the collection of unit quantity executed. Each worker must have one device attached or be filmed and identified. This will measure the hours on duty, the movements (gesture) and, the occupancy zones. At the same time, automated tools or equipment can provide the identification of the work process being executed. Further, the data obtained by sensors allows the measurement of external factors (e.g. temperature, and humidity). Based on the position, on the field of the item or element, it is possible to identify the work completion. Additionally, through image analysis is possible to interpret the work completion.

The electronic monitoring of construction workers can contribute for the assessment at the bottom of the ConocoPhillips Model. The At-risk behaviors and the Near Misses are the most difficult safety measurement approach as they depend of the human-observation notes usually conducted in a safety audit. Based on the location, trajectory, velocity and use of Personal protective equipment (PPE) At-risk behaviors might be measured. Also with the monitoring of the equipment and vehicles, it is possible to measure the Near Misses. For sure, the IT integration allows the information about the Recordable Injuries, Working Days Lost and Fatalities. The percentage of time inside the production zone could indicate more endeavors. The amount of time handling tools and equipment could indicate more effort. The interpretation of feelings by brain activity could indicate more motivation.



Performance Indicators	Device(s)	Application and Results	Main Application	Metrics
Units per Man-Hours (input per output)	Portables. Wearables. Images. Automated Systems	Directly and Indirectly	Direct workforce. Autometed tools and equipment	Units (m3, ton, etc.) / Man x Hour (M.h)
Value associated per Units (input per output)	Automated Systems	Indirectly	Autometed tools and equipment handling by the workforce	Monetary value (Dollar, Euro, etc.) / Units (kg, lts, etc.)
On-time completion and time variation	Portables. Images	Indirectly	Construction items and elements handling by the workforce	Time spent (hrs.) / Overall scheduled duration (hrs.)
Human resource management	Portables. Wearables. Images	Directly	Direct workforce. Indirect workforce	Man x Hour (M.h expected) / Man x Hour (M.h performed)
Quality control and rework	Portables. Wearables. Images	Directly and Indirectly	Direct workforce. Inspection workforce	Man x Hour (M.h spent in rework), (M.h spent in field inspection)
Percent complete and speed of construction	Portables. Wearables. Images	Indirectly	Construction items. Construction elements	Percentage Completed (work done detection)
Earned Man-Hours and values	Portables. Wearables. Images	Directly	Direct workforce. Indirect workforce	Man x Hour (Man worked hours)
Lost time accounting and identification	Portables. Wearables. Images. Automated Systems. Sensors	Directly and Indirectly	Direct workforce. Autometed tools and equipment	Man x Hour (M.h by impact factors detection
Punch list and Extra time	Portables. Wearables. Images	Directly	Direct workforce. Indrect workforce	Man x Hour (M.h spent in punch list tasks)
Safety (accident and hazard rates)	Portables. Wearables. Images. Automated Systems	Directly	Direct workforce. Autometed tools and equipment	M.h of At-risk behaviors detected. M.h of Near Misses detected
Absenteeism	Portables. Wearables. Images	Directly	Direct workforce. Indirect workforce	Man x Hour (M.h expected) / Man x Hour (M.h performed)
Motivation	Portables. Wearables. Images. Automated Systems. Sensors	Indirectly	Direct workforce. Autometed tools and equipment	Timing inside the production zone. Timing handling tools and equipment. Interpretation of feelings by brain activity

Figure 3: General Framework

4. Construction 4.0 based on Workers dimension

4.1 Integrated management KPIs model

The KPIs (worker-centered) detected by sensing technologies above presented are in an interactive way connected to the main constraints of project management. Project managers by controlling the construction projects based on these KPIs will be able, in early stages, to best-detected impacts in the project constraints, Figure 4. The type of building and its function drives the needed features and it delimits the project scope. As so, the tasks are connected with the function and have influence on the specifications, allowing the determination of the environmental impact of the construction. The environment negative impact is directly connected with the duration of the construction stage in terms of pollutants, as CO2 emissions, wastewater, dust and noise. Consequently, a more productive project is less aggressive to the environment. Labour productivity also drives the projects' time and cost. In this sense, all the KPIs that measure Man-Hours are connected with the above-cited constraints. In addition, quality defects and rework will drain project resources and increase its cost and time. Most important, a safe workplace mitigates accidents and consequent absenteeism, fostering workers' motivation.

4.2 BIM integration concept

Linking extra 'dimensions' of data to information models has the potential to provide a richer understanding of a construction project (Richard McPartland, 2017). BIM dimensions have been studied and developed in a way that the range of this methodology can fit the construction life-cycle (Wong and Zhou, 2015). The use of BIM during the construction stage as been most related with scheduling and supervision, dimensions closely related with the project constrains (Jang and Lee, 2018; Schwabe, Teizer and König, 2019).The aspects related with safety and risk also relate with project constrains and are being argued if they are part of the 4D or if constitute a new dimension (GhaffarianHoseini *et al.*, 2017). For the purpose of this work and in respect to BIM, the workers monitoring finds links with tasks/job, schedule and safety dimensions, a part of being considered or not the same. Following ongoing research related with product information to be set during construction (Mêda, Moreira and Sousa, 2019) and information strategies towards asset information management (Munir, Kiviniemi and Jones, 2019), COBie has been explored as the structure to support and manage all the non-graphical data. Due to this, the storage and management of relevant workers data to perform the KPI's, is being envisaged using COBie Job spreadsheet combined with activities. This will constitute an interesting framework towards the integration of workers monitoring on BIM (Borrmann *et al.*, 2018). Considering the open discussion related with the dimensions this can be found to be "WD" (workers dimension).

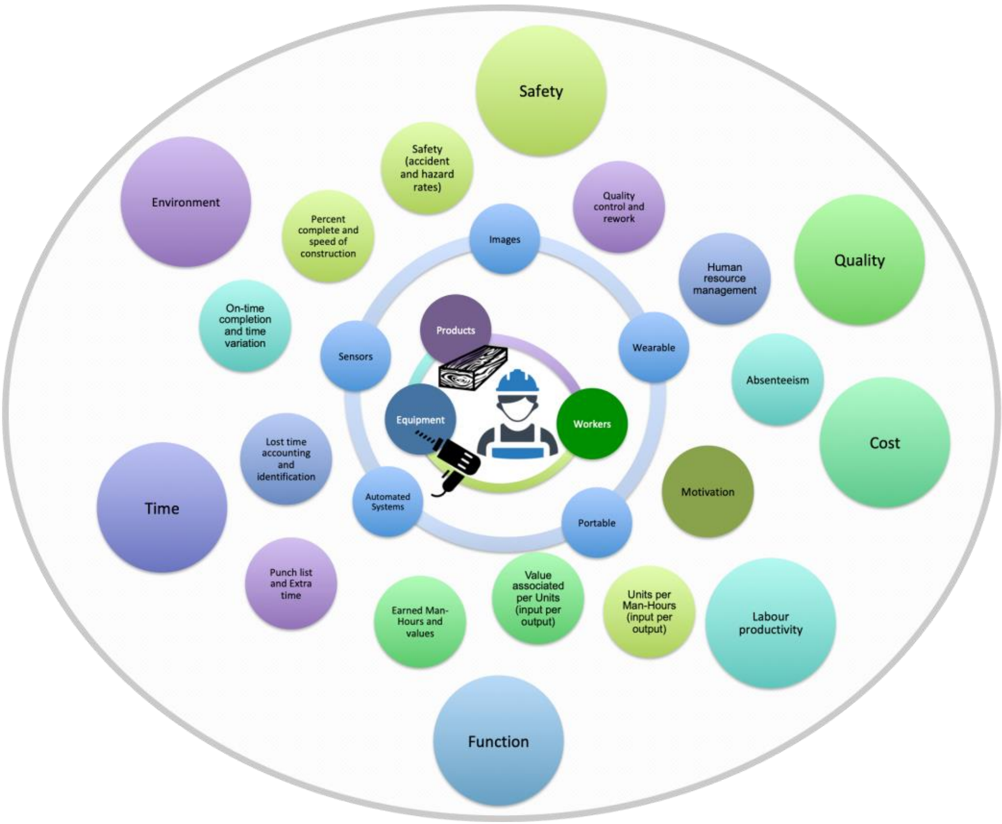


Figure 4: Integrated model

4.3 Smart contract integration concept

Finally, a construction smart contract centered on the workforce on duty is presented. The real-time workers-KPIs monitoring fosters an automatized and transparent contract administration. In addition, the whole process becomes more effective due to the automation of project updates (task order), service measurement and, payments (ICE, 2018). A collaborative project ecosystem is possible with the distributed information ledger between the distinguish stakeholders (e.g., client, contractor, subcontractor, vendors, suppliers, designers, consultants, certifiers, authorities, insurance, bank).

Figure 5 presents the concept that underlies the construction smart contract process. First, the data collected from the workforce on daily duties is processed by means of information technologies and techniques, being integrated into the BIM (WD-Workers Dimension). The Blockchain system, in a private network, makes the processing and validation of this information. Subsequently, the pre-defined contract rules are automatic played, the information is shared and specific routines are developed. Most importantly, the right information will be provided for the pre-establish stakeholder without the needed of accessing the BIM tools.

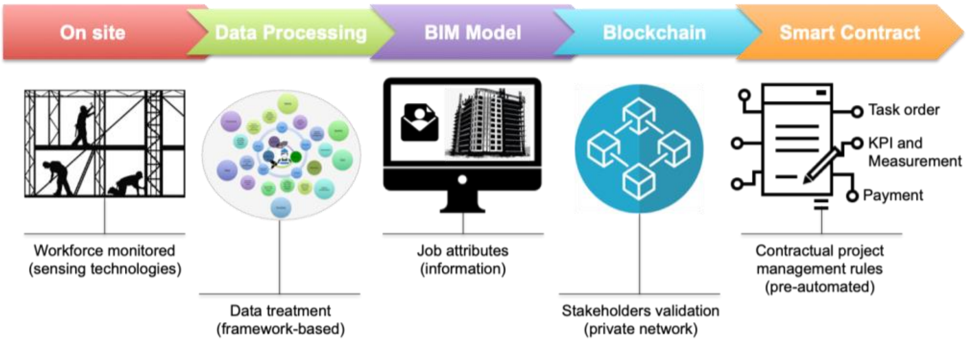


Figure 5: Smart Contract (WD - Workers Dimension)

Problems as unsolved claims and fast tracking during the execution of contracts affect the finance margin of contractors. At the same time SME cannot support late payments (ICE, 2018). Due the traceability of the most valuable information about the workforce, types of incentive fee contracts should be easier to structure. It is expected a lower risk of delays and over budgets. Furthermore, no more filtered information about poor safety conditions in the yards will be possible. Also, the BIM integration at the level of tagged build elements will allow a total quality assurance of the buildings.

As a result, all the construction production chain will earn more compliance and accuracy. Complex projects, principal de EPC (engineering, procurement and, construction) ones will take advances on the smart contracts application.

5. Conclusion

The construction industry is being pushed towards the adoption of innovations and new technologies. All aim to improve the performance of the outcomes and increase the productivity. The implementation of the presented megatrends will only succeed if there is a balanced approach between technology, processes and people. In what concerns the construction stage, the workers are main drivers towards innovation once they will handle and apply the new technologies on the construction processes. In addition, they constitute themselves a field for innovation through the use of devices that can measure performance in different dimensions. The Worker 4.0® (Calvetti, 2019) is the concept that aims to materialize the main principles and behavior of workers in a Construction 4.0 scenario.

The work developed led to the systematization of a framework to standardize electronic productivity metrics. Through this framework is becomes possible a streamlined selection and definition of Performance indicators based on the main applications, metrics and type of devices. This has direct implication with the characteristics of the works to be developed, the yard conditions, as well as the type of organization and willing of the workers. The integration of workforce-related data on BIM and the implementation of Smart contracts foster traceability, collaboration, and transparency, enhancing projects efficiency.

Empirical studies have been conducted in the CONSTRUCT/Gequaltec (Faculty of Engineering University of Porto) in order to develop and test methodologies of workforce electronic performance monitoring. The added-value of this work for the construction industry can be improved through the integration of other factors. These, in addition to the improved support for the selection of Performance indicators, may allow, among others, the integration with other technologies for processes not related with workers performance as well as guidelines and awareness for the training of workers.

References

Adrian, JJ 2004, *Construction productivity: Measurement and improvement*. Champaign. IL: Stipes Publishing.

Alder, GS 2001, 'Employee reactions to electronic performance monitoring: A consequence of organizational culture', Journal of High Technology Management Research, 12, pp. 323–342.

Borrmann, A, König, M, Koch, C & Beetz, J 2018, Building Information Modeling, Technology Foundations and Industry Practice. Springer.

Calvetti, D 2019, 'WORKER 4.0'. National brand number 616437, Portugal.

Chan, APC & Chan, APL 2004, 'Key performance indicators for measuring construction success', Benchmarking: An International Journal, 11(2), pp. 203–221.

Cheng, T, Mantripragada, U, Teizer, J & Vela, PA 2012, 'Automated Trajectory and Path Planning Analysis Based on Ultra Wideband Data', Journal of Computing in Civil Engineering, 26(2), pp. 151–160.

CIB Publication: 373, 2013 'Integrated Design & Delivery Solutions (IDDS)'.

Cox, RF, Issa, RRA & Ahrens, D 2003, 'Management's Perception of Key Performance Indicators for Construction', Journal of Construction Engineering and Management, 129(2), pp. 142–151.

Decree-law No 1592/2004 , Portugal .

Forum, WE 2016, 'Shaping the Future of Construction. A Breakthrough in Mindset and Technology', in World Economic Forum. Retrieved June, p. 2017.

Freibott, B 2013, 'Sustainable safety management: incident management as a cornerstone for a successful safety culture', in Safety and Security Engineering V. WIT Transactions on The Built Environment, pp. 257–270.

Gangolells, M, Casals, M, Gassó, S, Forcada, N, Roca, X & Fuertes, A 2009, 'A methodology for predicting the severity of environmental impacts related to the construction process of residential buildings', Building and Environment, 44(3), pp. 558–571.

GhaffarianHoseini, A, Zhang, T, Nwadigo, O, GhaffarianHoseini, A, Naismith, N, Tookey, J & Raahemifar, K 2017, 'Application of nD BIM Integrated Knowledge-based Building Management System (BIM-IKBMS) for inspecting post-construction energy efficiency', Renewable and Sustainable Energy Reviews, 72(April 2018), pp. 935–949.

Groover, MP 2007, Work Systems and the Methods, Measurement, and Management of Work. Pearson Prentice Hall.

ICE 2018, Blockchain Technology in the Contruction Industry. London. Available at: ice.org.uk.

ISO 12006-2, 2015 'ISO 12006-2:2015 Building construction - Organization of information about construction works - Part 2: Framework for classification'. International Organization for Standardization.

ISO 450001, 2018 'ISO 45001:2018 - Occupational health and safety management systems'. International Organization for Standardization.

Jang, S & Lee, G 2018, 'Process, productivity, and economic analyses of BIM–based multi-trade prefabrication—A case study', Automation in Construction, 89(December 2017), pp. 86–98.

McKinsey (2017) Reinventing Construction: a Route To Higher Productivity, McKinsey. Available at: https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/reinventing-construction-through-a-productivity-revolution. [24 April 2019].

Mêda, P, Moreira, J & Sousa, H 2019, 'Delivering COBie with ProNIC—compliance and implementation', eWork and eBusiness in Architecture, Engineering and Construction, pp. 215–222.

Munir, M, Kiviniemi, A & Jones, S 2019, ‘Building Information Modelling (BIM) value realisation framework for asset owners’, eWork and eBusiness in Architecture, Engineering and Construction, (September), pp. 313–320.

Navon, R & Goldschmidt, E 2003, ‘Can Labor Inputs be Measured and Controlled Automatically?’, Journal of Construction Engineering and Management, 129(4), pp. 437–445.

PMI 2017, A guide to the project management body of knowledge : (PMBOK guide). Edited by S. edition. Newtown Square, Pa.: Project management Institute.

Richard McPartland 2017, BIM dimensions - 3D, 4D, 5D, 6D BIM explained | NBS, NBS. Available at: https://www.thenbs.com/knowledge/bim-dimensions-3d-4d-5d-6d-bim-explained [24 April 2019].

Schwabe, K, Teizer, J & König, M 2019, ‘Applying rule-based model-checking to construction site layout planning tasks’, Automation in Construction, 97(November 2017), pp. 205–219.

Sink, DS 1985, Productivity management: planning, measurement and evaluation, control, and improvement. John Wiley & Sons.

Sousa, HJC & Magalhães, PNM 2017, ‘Estratégias para a fileira da construção nacional – síntese de visões e resultados de implementação’, in International Congress on Engineering.

Wong, JKW & Zhou, J 2015, ‘Enhancing environmental sustainability over building life cycles through green BIM: A review’, Automation in Construction, 57, pp. 156–165.

Yang, J, Park, MW, Vela, PA & Golparvar-Fard, M 2015, ‘Construction performance monitoring via still images, time-lapse photos, and video streams: Now, tomorrow, and the future’, Advanced Engineering Informatics, 29(2), pp. 211–224.

Measuring and Improving the Productivity of Construction's Site Equipment Fleet: An integrated IoT and BIM System

Mohamad Kassem[1]*, Kay Rogage[1], James Huntingdon[1], Gabriel Durojaye[2], Noemi Arena[2], Graham Kelly[3], Thomas Lund[3] and Terence Clarke[4]

[1]Department of Mechanical and Construction Engineering, Northumbria University Newcastle, UK.
[2]Costain Group, London, UK.
[3]BIM Academy, Newcastle, UK.
[4]Buildstream, Brooklyn, US.
*email: mohamad.kassem@northumbria.ac.uk

Abstract

Annual productivity growth within Construction has increased by just 1% in over 20 years (McKinsey, 2017). A key contributor to this performance issue is associated with the management of construction's equipment fleet. Site equipment represent a significant percentage of the total cost of projects; are a critical 'bottleneck' resource that is linked to delays, and a major contributor to on- and off- site congestion and air pollution. Their effective management represent a key opportunity for economic, environmental and safety efficiency gains.

Research and development efforts aiming to address this challenge are on the rise in both industry and academia. Much of existing studies try to exploit opportunities made available by the Internet of Things (IoT). Studies are addressing accidents prevention, measurement of operational efficiency, monitoring equipment health, and improving equipment deployment. Equipment default telematics systems are increasingly providing important operational data (e.g., working hours, fuel consumption, fault code, etc.) but these have many limitations such as: they are restricted to heavy equipment; they do not capture all data required for effective management of construction equipment fleet, and data is not aggregated from across disparate systems to enable intelligent decisions. Moreover, data from IoT systems is not linked to any Building Information Modelling (BIM) environment (e.g. 4D BIM), making it challenging to contextualise the operation of construction fleet equipment and to inform more intelligent and proactive deployment decisions.

This paper proposes an integrated IoT-BIM system for the management of site equipment. Eight interviews were held with experts from the largest infrastructure projects in the UK to identify the key challenges facing site equipment fleet and the key use cases to be addressed. A review of existing telematics systems was performed to identify their capabilities and limitations in relation to an integrated IoT-BIM solution for the identified use cases. An early architecture of the proposed IoT-BIM system is described. The proposed system requires i) the collection of data from disparate telematics systems and the development of tailored IoT devices for data generation and collection, ii) machine learning algorithms to interpret the data for the use cases' decisions, and iii) data and information from both the IoT and the machine learning unit into the 4D BIM environment and the dashboard visualising the performance for the selected use cases.

This work is part of a joint industry-academic effort co-financed by Innovate UK as a feasibility study project under their 'Increase Productivity, Performance and Quality in UK Construction' competition.

Keywords: BIM, IoT, Machine Learning, Productivity, Use Case.

1. Introduction

Advances in digitalisation are enabling new ways for investigating rooted challenges with the construction sector. Together BIM, which is the current expression of digital innovation within the construction sector (Succar and Kassem, 2015), and the Internet of Things (IoT) are transforming the way built assets are designed, constructed and operated. One such a challenge at the construction phase is the effective management of site equipment fleet. Exploiting digital advances for this challenge is motivated by the significant incidence of construction equipment on the cost and schedule of projects and the opportunity of increasing their productivity (e.g. utilisation rate, reliability/availability, etc.) and reducing their environmental, health and safety impact. The prevailing current practices in management of construction equipment management are highly dependent on individuals' experiences. Data on construction equipment operations is recorded by contractors sporadically, if at all. The data is stored in different cost centres such as a project site or a fleet, forming siloes or 'information islands' that are hardly communicated, or known, to other decision-makers. Finally, comprehensive data sets that can cover the entirety of construction equipment fleet on site is still lacking despite being highly demanded by fleet project managers and executives (Niu et al., 2017).

This paper proposes an integrated IoT-BIM system for effective management of construction site equipment fleet. Section 2 summarises some of the key studies addressing site equipment productivity through digital advances. Section 3 reveals the findings from 10 interviews with experts from major infrastructure projects in the UK about current practices, key challenges, and top use cases. Section 3 briefly describes the proposed framework. Section 4 discusses and concludes the paper.

2. Literature review

The upsurge in research investigating new ways and systems for improving site equipment fleet management is motivated by the advancement and affordability of IoT sensing devices and increased adoption of BIM. Studies available in the literature are addressing various aspects related to the management of site equipment including: equipment usage patterns, fuel consumption and carbon emission, safety and access to equipment, routine and preventive maintenance, servicing strategies (i.e. repair or replacement), procurement strategies (i.e. buy or lease), fleet allocation/deployment, and fleet tracking and localisation (Niu et al, 2017). This section provides a summary of the key studies in this realm.

Fang et al. (2016) developed a system by combining BIM and cloud enabled Radio Frequency Identification (RFID) localization systems to enable the localisation of indoor mobile construction resources. The testing on site and discussions with site engineers and managers indicated that the proposed RFID indoor localization system has a great potential in practical applications such as site security control, safety management, and first responder rescue. Zhou and Ding (2017), through combining RFID, tracking technology, ultrasonic detection technology, and infrared access technology into a three-tier network architecture, developed a system that assisted site workers in changing their risky behaviours and accident avoidance in underground construction sites. Zhifeng et al. (2016) developed a similar system for mobile cranes that facilitated remote monitoring and accident analysis. Kanan et al. (2018) developed, by combining sensing systems based on three techniques (i.e. radio frequency, directional antennas, and ultrasound waves), an IoT-based autonomous system for monitoring the safety of workers on site. This sensing system was installed on the rear of site equipment and used in conjunction with a workers' wearable device that includes a radio transceiver (transmitter/receiver), a wake-up sensor, an alarm actuator, and a General Packet Radio Service (GPRS) module. The combination of the two systems helps in monitoring, localising, and warning site labourers of proximity dangers.

Lu et al. (2011) explored the application of Radio Frequency Identification (RFID) technology in assisting the management of material, men and machinery on site. In relation to machinery on site, potential applications that were identified include tracking of machines and tools, machine operation permission systems and utilisation records, and machine maintenance records.

Zhong et al. (2014) proposed an IoT system called 'Safety Management System for Tower Crane Groups'. The system is used to detect the operating status of each tower by a set of customized sensors, including horizontal and vertical position sensors for the trolley, angle sensors for the jib and load, tilt and wind speed sensors for the tower body. The sensor data is collected and processed by the Tower Crane Safety Terminal Equipment (TC-STE) installed in the driver's operating room. Wireless communication between each TC-STE and the Local Monitoring Terminal (LMT) at the ground worksite were fulfilled through a Zigbee wireless network. LMT can share the status information of the whole group with each TC-STE, while the LMT records the real-time data and reports it to the Remote Supervision Platform (RSP) through GPRS. Based on the global status data of the whole group, an anti-collision algorithm was executed in each TC-STE to ensure the safety of each tower crane during construction. Remote supervision was fulfilled using the client software installed on a personal computer (PC) or smartphone. Niu et al (2017) proposed a system that enabled the collection of site equipment's operational data and the production of analytics for their management. The two key components of the proposed systems were: (1) a smart chip that integrates various sensing and communication modules for proactively collecting and exchanging from daily equipment operations; and (2) a data analytics platform for data storage, visualization and analytics. The approach used by the authors consisted of using the concept of "Smart Connected Objects (SCO)" where construction resources (e.g., machinery, tools, devices, materials, and even temporary or permanent structures) are made smart by augmenting them with sensing, processing, and communication abilities. With this they have autonomy and awareness, and can interact with the vicinity to enable better decision making. Ahn et al. (2013) developed a system for the operational efficiency and environmental performance of site equipment. Controlling the operational efficiency of equipment is key to managing and improving the environmental performance of construction operations. Their method was based on using vibration signal analysis to monitor the operational status of equipment.

Aslan et al. (2012) developed a system for enhancing the operational productivity of site equipment by combining GPS, WSN, and web applications. Their focus was to provide information on raw data integration and productivity data analysis for the development of fleet management metrics to identify areas of improvement (e.g. guideline to managers, effective equipment operations, resilience and flexibility improvement, and cost reduction).

Said et al. (2015) developed a telematics-based equipment health-monitoring framework to support fleet service managers in using telematics data in their predictive maintenance programs. The framework consisted of two modules: (1) the health parameters processing and visualization (HPPV) module; and (2) an equipment failure hazard estimation (EFHE) module. A recent review of studies in this area is also available in Zankoul et al. (2018).

Object recognition techniques are currently used for tracking construction processes against BIM data. Wu et al. (2009) use object recognition to compare construction-site photographic images against 3D BIM models to assess construction processes. This approach extracts objects of interest such as concrete columns from site images and uses advanced imaging algorithms to compare 3D objects from the BIM design model to detect objects within the site images.

Gledson and Greenwood (2016) state that the key advantage of 4D BIM is the handling and communicating of information to improve understanding of planned activities. Hakkarainen, M. et al (2009) discuss the use of 4D modelling and augmented reality to check planned vs actual on site. Sulankivi, K. et al (2013) discuss the automatic recognition of health and safety issues in 4D modelling during the design process. But there is currently lack of studies looking at linking live data to models to show what is happening live on a site, and this paper is starting to explore this potential.

Some of the key limitations of existing studies include: limited input from the industry in relation to the required use cases; use of a limited set and types of data; limited use of machine learning to transform/optimise decisions; lack of integration with BIM environment to contextualise the deployment of equipment and inform the planning/deployment process of equipment; and limited development in dashboards to visualise equipment performance from across the entire equipment fleet.

3. Review of telematics systems

Telematics refers to any integrated use of wireless communications, vehicle monitoring systems, and location devices to provide real-time spatial and performance data of fleet machines (Aslan et al., 2012; Said et al. 2015). Application of telematics in construction site equipment is a way not only to assess existing equipment productivity but also to provide a baseline for future productivity improvement, optimising operation planning, and establishing long-term strategic organisational objectives (Aslan et al., 2012). A usability review of telematics systems for construction equipment fleet management is included in Jagushte (2017). The commonly collected parameters by such systems include: actual machine operating hours, machine location, machine health, and fuel consumption. The review revealed challenges that affect the use of these systems; such as the difficulty in storing the data collected and performing the required analytics (e.g. interpretation of high volume of data), and acceptance of the technology by professionals who deem to be implementing good equipment fleet management practice. Some standards and third party telematics systems providers are emerging to develop a more universal solution to the data collection from across the wide and varied equipment included in a site fleet. Some international standards such as the ISO 15143-3 (previously known as the AEM/AEMP Telematics Standard) are also emerging to address the challenges of collecting data from mixed fleet Telematics systems.

The authors have performed their own review of commercially available telematics by Original Equipment Manufacturers (OEM). The systems were anonymised (i.e. Supplier 1, 2, etc.) for confidentially and commercial purposes. The results of the review are summarised in Table 1.

The performance areas measured are included in the heading of Table 1. The review found that there is often inconsistency in the reporting of such performance areas. For example, 'fuel used' and 'engine on hours' are reported cumulatively in some systems but are reported daily in other systems. 'Location' is provided at a variable point in time during the day across the different systems. Distance is reported as the cumulative distance travelled in some systems while distance travelled during a timeframe by other systems. Load factor which is the capacity at which the equipment was working compared to its maximum rating (such as maximum weight carried) or output function, an important key performance indicator for measuring productivity is not measured by existing telematics systems. In the vein is the 'working' function which measures the amount of time the asset spent in each working state, idle, travelling or working. Fault data are captured in one system only. Most of the measured data is not available in real time or near real-time and most system, with the exception of few, have reliability issues, characterised by issues related to transmission of data and accuracy of transmitted data.

Table 1 Review of telematics systems

OEP	**Data Reliability**	**Fuel Used**	**Fuel Remaining**	**Engine on hours**	**Idle Hours**	**Location**	**Distance**	**Load Factor**	**Working**	**Fault Data**
Supplier 1	97%	Y	Y	Y	Y	Y	N	N	N	N
Supplier 2	95%	N	N	Y	N	Y	N	N	N	N
Supplier 3	99%	Y	Y	Y	Y	Y	Y	N	N	Y
Supplier 4	41%	Y	N	Y	N	Y	Y	N	N	N
Supplier 5	56%	Y	N	Y	Y	Y	N	N	N	N
Supplier 6	77%	Y	N	Y	N	Y	N	N	N	N
Supplier 7	29%	Y	Y	Y	Y	Y	N	N	N	N
Supplier 8	82%	Y	Y	Y	N	Y	N	N	N	N
Supplier 9	<5%	N	N	N	N	Y	N	N	N	N

4. Interviews with experts

As identified in Section 3, there are a range of telematics systems available with which to measure and monitor construction site plant and equipment (PE) operation and performance. However, questioning what data should be collected and for what purpose (i.e. defining use cases) has been fundamental to designing an appropriate study for application of IoT devices and data services. The current research therefore carried out interviews with a range of stakeholders to reveal the most viable or beneficial use cases to which IoT devices and data analysis should be applied.

The questioning framework focused on issues that are known to impact time and costs within construction projects, including: planning and scheduling of PE (budgeting, specification), management of PE onsite (logistics to and from site, movement onsite, fuel/refuelling issues), hiring and supply chain processes, management of statutory requirements (e.g. carbon reduction), utilisation of PE, and management of failure and maintenance.

The selected interviewees either directly interact with PE (including specification, scheduling, and operation) or where the role did not directly interact with PE was impacted by the performance and cost of PE. The roles included project director, project manager, plant & equipment manager, organisational development professionals (lean practitioners), site foreman, surveying and monitoring staff, health and safety professionals and compliance managers.

All interviewees worked for the Costain Skanska Joint Venture (CSJV) at the High Speed Rail 2nd Phase (HS2). This particular programme of work involved excavation and enabling works, demolition and ground remediation. Key challenges cited by the interviewees included: operation of PE within confined and covered work areas, archaeological sensitivities (the site is a burial ground which required exhumation of over 10,000 bodies), is a Central London location, and where the client (UK Government) has mandated over 400 undertakings and assurances (UAs) which require self-management and reporting by CSJV.

A summary of the use cases elicited is presented in Table 2. The summary represents a consensus of use cases and identification of any associated metrics that are recorded/reported during the contract by the CSJV. This data is to be used as the basis for determining how and where the IoT hardware will be deployed, i.e. which plant or equipment, work actions to be monitored, and measures/features to be recorded within the capabilities of the sensing devices; namely vehicle engine activity, video surveillance of moving parts, and acoustic anomaly monitoring (i.e. fault detection.) A detailed account of the IoT hardware used for this project is presented in Section 5.

Use cases 1, 2 and 3 (Table 2) have been chosen for application of IoT devices and data streaming/analysis.

Use case 1: Total volume of material excavated: A key metric cited by the interviewees is the volume of spoil being excavated and removed from site. This is an output based measure against which the project was originally budgeted and was evaluated daily during the project. Complications identified the inability to make use of pre-existing telemetry fitted to PE due to inconsistencies and incompatibilities of systems. For example, lorry pay load scales were found to be unreliable. Supplementary measuring devices were therefore employed including laser scanning by drones to measure topology changes from which volume removed was estimated. Furthermore, the granularity of data measurement meant that productivity and utilisation of individual PE was not possible. Manual measurements are reported daily for each work zone. The current research aims to provide live streaming of productivity rates for individual PE assets. It was reported that a major challenge in effective estimation (budgeting and costing) prior to commencement of the work was how to quantify the productivity of archaeologists supported by mechanical dig equipment. This has never been accurately quantified prior to this project. The site being a burial ground also required sensitive excavation with often labour intensive elements to ensure respectful removal of bodies. A target of 1.25 metres cubed per archaeologist per day was set. Management of labour numbers and PE utilisation is therefore difficult to measure and monitor. The current research will therefore aim to improve the granularity and quantification for mixed labour-mechanised utilisation rates.

Table 2 Key plant and equipment measures and use cases

	Use case	Measure	Count
1	Productivity (archaeologist excavation rates per labour unit (1.25m^3 /day/head)); PE utilisation rate	Total material volume (m^3) removed	3
2	Audit (Control Board reports); PE specification versus utilisation rate	Cost/budget tracking	3
3	Progress reporting (Control Board); lean management (behavioural change analysis); scheduling	Job/task completion rate (% measure assigned) (planned versus actuals)	3
4	Traffic management planning (offsite logistics)	PE location	3
5	Monitoring and reporting undertakings and assurances; breach notifications; PE and operator fitness for purpose onsite; self-management capability assurances	Consents/compliance measure (e.g. emissions, noise)	3
6	Health and safety	Risk hours saved	1
7	Sustainability of construction, environmental compliance	Fuel/battery efficiency	1

* Count represents the number of interviewees making reference to the identified use case.

Use case 2: Control board monitoring. Audit of PE use is carried out at daily and weekly intervals by drawing data from disparate sources. The Control Board use a business intelligence (BI) software package to keep track of utilisation of PE and cost management. Data is imported to the BI from an array of sources including spreadsheets, manual reports and available telemetry and aggregated to project level which is a cumbersome and time-consuming approach. The current research intends to look at how asset specific utilisation measurements can be formed in to a continuous and synchronous dataflow, where data is live streamed and aggregated to provide meaningful project measures. This will provide a high level of connectivity between individual assets and overall project outcomes to improve PE specification, deployment and utilisation.

Use case 3: Project tracking. The final use case to be applied using IoT will be 'Progress Reporting'. A condition of the contract is for the CSJV to communicate progress with the client on a regular basis. Such evaluation of planned works versus actuals forms a significant value proposition for the relationship between IoT and 4D BIM modelling. The current research aims to assess the feasibility of providing snap-shot analysis of project progress and live PE tracking. Such visual inspection capabilities would afford decision-makers a powerful tool with which to identify bottle-necks, conflicts and clashes on projects which would be a major break-through in achieving efficiencies and stakeholder engagement.

The remaining use cases; traffic management planning, UAs monitoring, health and safety and business improvement (sustainability) have not been taken forward for research at this time. These use cases were determined to require more complex data measurements than could be supported by the IoT devices available.

5. Proposed approach

The proposed approach (Figure 1) is described in four parts: IoT hardware; asset inventory and business intelligence dashboard; machine learning; and 4D BIM.

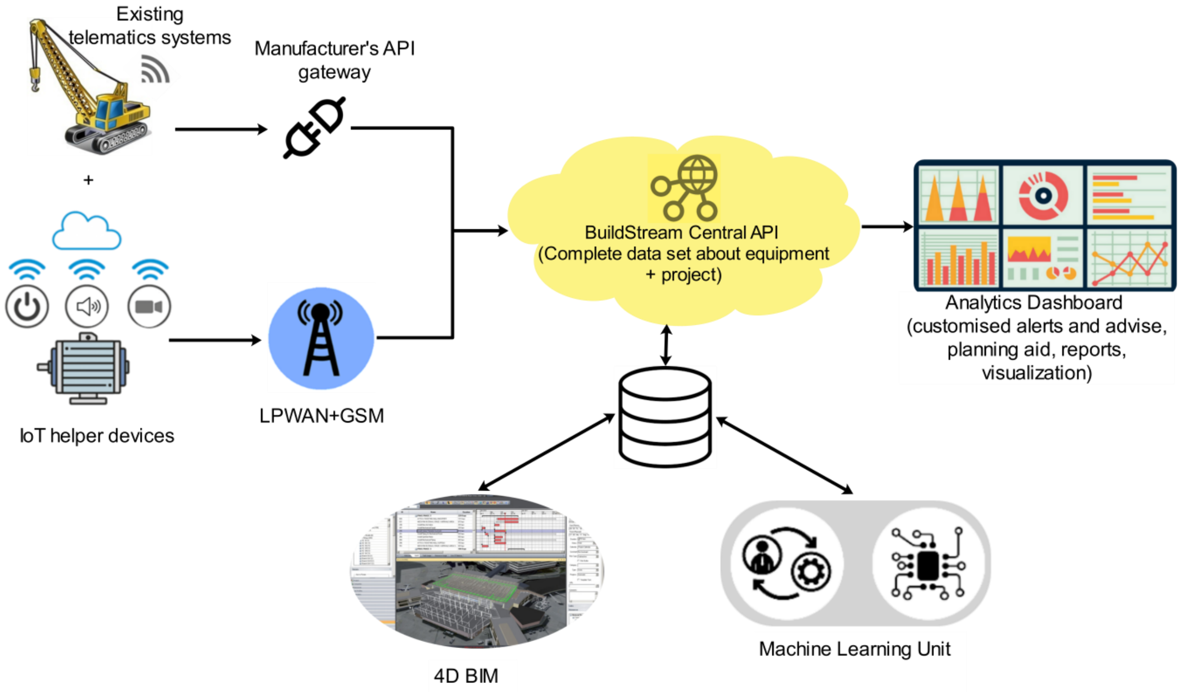


Figure 1. A simplified architecture for the system

The IoT device: includes a data logger, a camera, a microphone and a modem which allows the device to communicate data via GSM networks. The information is sent to the cloud-based database and can be used by the various modules (4DBIM, MLU) and the results are visualised on the web app.

The asset inventory and business intelligence dashboard (Figure 2): collates all existing data from telematics systems already installed on the equipment assets through API connections, providing one consolidated location for this information, which is then put into the context of the specific project. The data is stored on AWS servers and the web app / dashboard pulls the data from AWS into the front-end application. Individual assets, or groups of assets can be analysed by the project teams to determine areas of interest where operational interventions can be made to increase the efficiency of site operations.

The machine learning unit: The feasibility of identifying (either predicting a future state or inferring a current state) of PE using machine learning is being explored in this project. With reference to the use cases identified in Section 4, data sets are being evaluated that would support the prediction or inference of productivity and utilisation of PE; where productivity might be a measure of 'volume of soil excavated/unit/hour' and utilisation is a measure of the actual 'working state /unit/hour'.

The IoT hardware: measures three data items: location (via GPS), audio (via microphone), and vision (via camera). It therefore has three data sets which can be used to predict/infer productivity and utilisation. For the purpose of this paper, only the video stream data is being used to train a supervised learning ML algorithm by segmenting existing video footage of three classes of digger activities (Figure 3). Video segments are labelled with the activity (or class) that is being observed within the segment. A multi-class classification is being sought with three classes: 'working – digging', 'working – no digging', 'idling', where the algorithm is predicting one class from the three discrete classes.

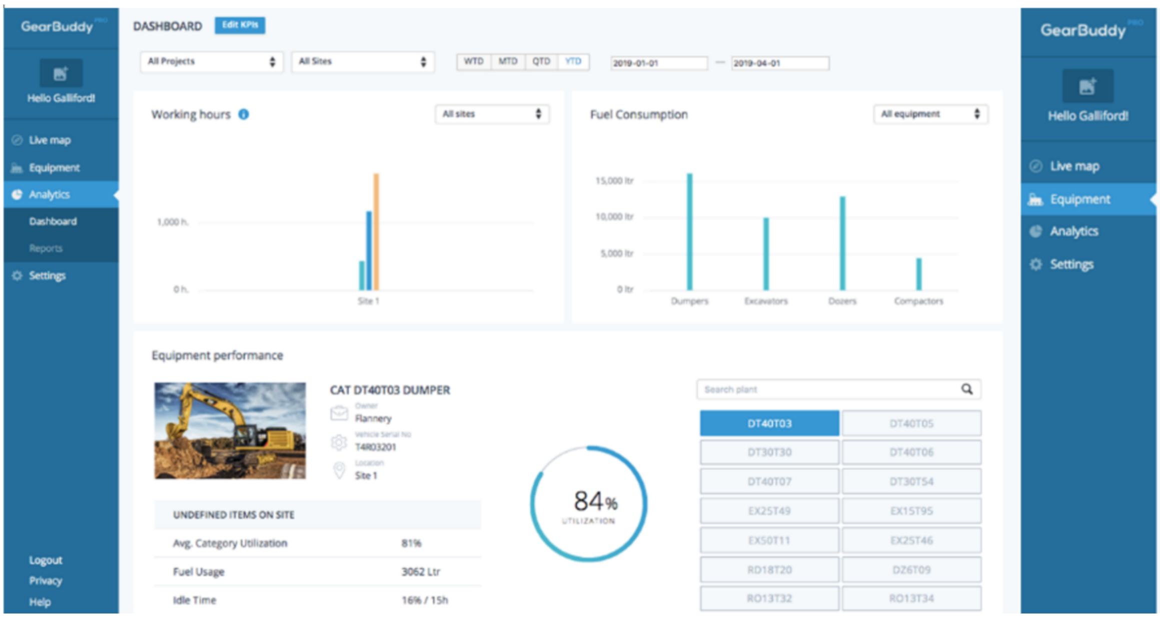


Figure 2. Collation and visualisation of data from site equipment fleet

Key challenges that the current project faces is the volume of data, i.e. the number of video segments required to deal with the complexity of the problem of class inference. The classes are similar to each other in appearance. For example, the motion of a 'digging arm in soil' is subtly different from a 'digging arm simply moving to position'. Based on classical rules for ML vision algorithms, the project is seeking more than1000 video examples per class. This must also include a diverse range within the problem space for each class (e.g. 'working – digging'), this might include: different operating environments, i.e. different ground colours, different light levels, wet/dry ground; different manufacturer arm types, or different camera angles, video resolution and frames per second. Once the classes have been detected, the system make this data available which can then be converted in productivity measurement and PE utilisation rates as described in the Use Cases table. This approach represents an improvement compared to the existing telematics solutions where (1) such granular measurement is not possible; and (2) data is not available in one consolidated platform. Moreover, data models from the IoT devices and 4D BIM model will be created and tested against the trained model to make best fit predictions on the likelihood of changes to the construction project process. The project will not, at this stage, be looking at deploying this full ML solution, i.e. that is to build a data pipelines that extracts data from the IoT devices, transforms, predicts and imports to 4D BIM. This will be an offline activity in order to evaluate the accuracy of the proposed end to end solution in meeting the objectives of the use cases.

4D BIM: To provide context for the deployment and productivity of PE within the planning process and enable proactive decisions about their deployment, links with 4D BIM plans for site management are proposed utilising a commercially available 4D BIM software. Links will be explored using both live data and offline data from the IoT sensors. Live data into the 4D BIM model will be used to link and visualise which equipment is active on specific tasks within the project (e.g. how many and which excavators are working on digging a hole activity, and how many and which access platforms are working on installing cladding activity). This will support in the reporting of progress, the utilisation of PE on site and the use of visual method statements. A plant and equipment library will be also built to provide a realistic representation of the equipment within the 4D schedule. Use of this 4D BIM linked environment over time will provide sufficient offline data for further intelligent decisions in future. For example, the trained model can be used to make predictions on the likelihood of changes to the construction project process associated with PE. This capability will require the further ML functionalities to learn about the relationship between PE utilisation and project progress from images generated by the augmented 4D BIM system.

6. Discussions and Conclusions

Construction equipment is a critical resource in most construction projects. Current inefficiencies in management of site equipment fleet, recognised in both research and practice, is a key contributor to the gap in productivity performance of construction projects and the whole sector. Advances in digitalisation enabled by BIM and IoT, accompanied by increased affordability of sensing devices, are opening new ways to investigate this challenge. In response to this challenge and the key shortcomings of both existing studies and commercially available telematics systems, this paper proposed an integrated BIM-IoT system for Measuring and Improving the Productivity of Construction's Equipment Fleet. Limitations in existing studies included limited engagement with the industry in relation to the use cases addressed (e.g. identification and prioritisation of use cases); use of a limited set and types of data; limited deployment of machine learning to transform/optimise decisions; lack of integration with BIM environment; and limited development in dashboards to visualise equipment performance from across the entire equipment fleet. Commercially existing telematics systems have an inconsistent approach to data capture and reporting; capture a limited number of data items that are not sufficient to measure the productivity of either an individual equipment or an entire fleet; and are affected by reliability issues related to transmission of data and accuracy of transmitted data. The proposed system integrate data from an entire fleet in a near real-time manner and enables the measurement of equipment productivity. The proposed system was tailored for three of the uses cases that were most frequently mentioned by the 10 experts interviewed. The system consisted of IoT hardware; asset inventory and business intelligence dashboard; machine learning; and 4D BIM. Each of this component and the architecture of the whole system was described. The current progress in the development of the tool include the IoT device, the dashboard and the machine learning unit. A brief demonstration of the prototype was provided. It showed how the system uses the video stream data to predict three classes, 'working – digging', 'working – no digging', and'idling', of equipment status using a supervised learning ML algorithm. The dashboard collating data from across an entire fleet was also demonstrated. Future development will include (1) assessment of the accuracy of the productivity measurement achieved by benchmarking predicted against actual. This work is required to complete Use Case 1 and will necessitate the collection of a significant video footage to address the challenges facing the implementation of the ML algorithm; (2) addressing Use Cases 2 and 3 and completing the implementation of links with the 4D BIM environment; and (3) holistic testing of the whole system on an entire site equipment fleet.

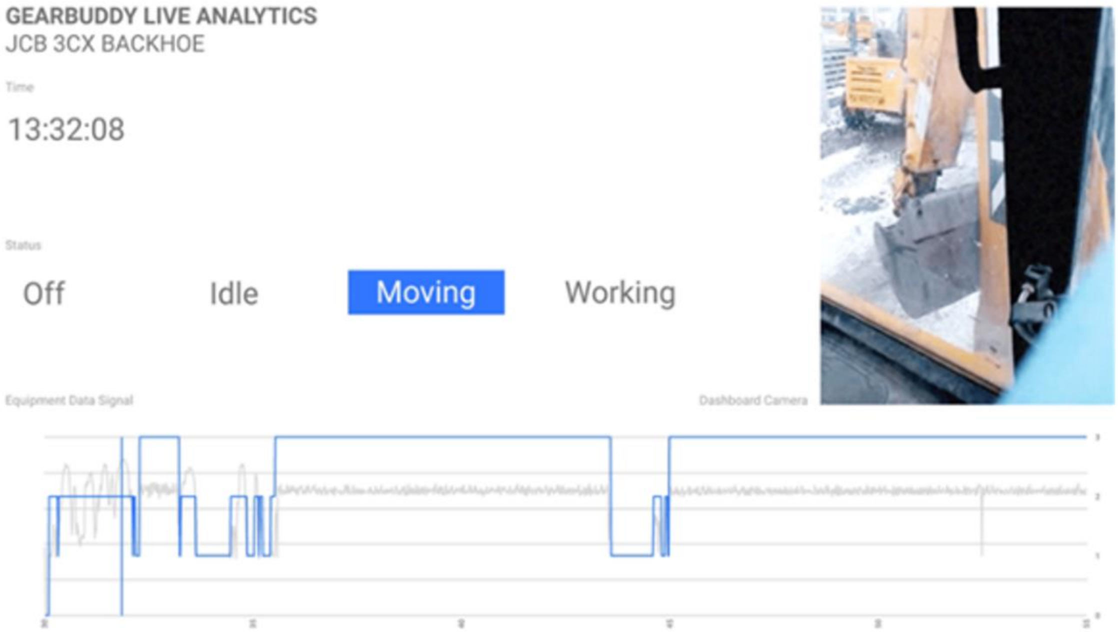


Figure 4. Supervised learning ML algorithm predicting three classes of digger activities.

Acknowledgements

The research is supported by Innovate UK (Grant Number: 22724, Project title: Optimising equipment use in construction with BIM, IoT and data analytics) under the ‘Increase productivity, performance and quality in UK construction’ competition. We owe gratitude to the industry experts who provided invaluable input and insightful discussions.

References

SUCCAR, B. & KASSEM, M. 2015. Macro-BIM adoption: Conceptual structures. *Automation in Construction*, 57, 64-79.

ZANKOULA, E., KHOURY, H., SALHABA, D., and ANTARA S. 2018. A review on Internet of Things solutions for enhancing construction equipment fleet productivity. *Proceedings of the Creative Construction Conference* 2018, 30 June - 3 July 2018, Ljubljana, Slovenia.

McKINSEY 2017. Reinventing Construction: a route to higher productivity. McKinsey Global Institute, available at: https://www.mckinsey.com/mgi/overview

ZHIFENG, M., Yahui, F. and Zhi, X.Remote monitoring system of mobile crane based on Internet of Things, *Journal of Hoisting and Conveying Machinery*, 2016.

KANAN, R., ELHASSAN, O. and BENSALEM, R. (2018). An IoT-based autonomous system for workers' safety in construction sites with real-time alarming, monitoring, and positioning strategies, *Automation in Construction*, no. 88, pp. 73-86, 2018.

ZHOU, C. and DING, L. (2017). Safety barrier warning system for underground construction sites using Internet-of-Things technologies, *Automation in Construction*, no. 83, pp. 372-389.

FANG, Y., CHO, Y., ZHANG, S. and PEREZ, E. (2016). Case Study of BIM and Cloud–Enabled Real-Time RFID Indoor Localization for Construction Management Applications, *Journal of Construction Engineering and Management*, 142(7), 05016003.

ZHONG, D., LV, H., HAN, J. and WEI, Q. (2014). A Practical Application Combining Wireless Sensor Networks and Internet of Things: Safety Management System for Tower Crane Groups, *Sensors*, pp. 1374-1381.

LU, W., HUANG, G.Q. and LI, H. (2011). Scenarios for applying RFID technology in construction project management, *Automation in Construction*, pp. 101-106, 2011.

NIU, Y., LU, W., LIU, D., CHEN, K. and XUE, F. (2017). A Smart Construction Object (SCO)-Enabled Proactive Data Management System for Construction Equipment Management, *Computing in Civil Engineering*, pp. 130-138.

AHN, C., LEE, S. and PEÑA-MORA, F. (2013). Accelerometer-Based Measurement of Construction Equipment Operating Efficiency for Monitoring Environmental Performance," in *ASCE International Workshop on Computing in Civil Engineering*, Los Angeles, California.

ASLAN, B., and KOO, D. (2012). Productivity enhancement for maintenance equipment operations using telematics technology. *Construction Research Congress*, ASCE, West Lafayette, IN, 971–980.

SAID, H., NICOLETTI, T., and PEREZ-HERNANDEZ, P. 2014. Utilizing Telematics Data to Support Effective Equipment Fleet-Management Decisions: Utilization Rate and Hazard Functions. *Journal of Computing in Civil Engineering*, 30 (1).

JAGUSHTE, V.J. 2017. Usability Review of Telematics for Construction Equipment Fleet

Management. Master Thesis, University of Florida.

WU, Y., KIM, H., KIM, C., & HAN, S. H. (2009). Object recognition in construction-site images using 3D CAD-based filtering. *Journal of Computing in Civil Engineering*, 24(1), 56-64.

HAKKARAINEN, M., WOODWARD, C. and RAINIO, K., 2009, October. Software architecture for mobile mixed reality and 4D BIM interaction. In *Proc. 25th CIB W78 Conference* (pp. 1-8).

SULANKIVI, K et al. (2013). Utilization of BIM-based automated safety checking in construction planning. In *Proceedings of the 19th International CIB World Building Congress*, Brisbane Australia (pp. 5-9).

GLEDSON, B. and GREENWOOD, D., 2016. Surveying the extent and use of 4D BIM in the UK. Journal of Information Technology in Construction (ITcon), 21, pp.57-71.

Trends in BIM and IoT for Reactive Maintenance

Beatriz Campos Fialho[1], Ricardo Codinhoto[2], Márcio Minto Fabricio[1]

[1]The University of São Paulo, Institute of Architecture and Urbanism, São Carlos, Brazil

[2]The University of Bath, Department of Architecture and Civil Engineering, Bath, United Kingdom

[*]email: beatriz.fialho@usp.br

Abstract

It is widely acknowledged in the literature that a buildings' operational phase is directly related to the success of the business it supports. Building operation demands continuous efforts to reduce waste and operational costs while also improving service delivery. Of particular importance is the management of the Reactive Maintenance (RM) that if not managed efficiently can directly impact production lines and building user experiences, interrupting work and service provision. Building Information Modelling (BIM) and Internet of Things (IoT) solutions and devices have demonstrably delivered efficiency gains for some Facilities Management (FM) activities such as workplace management, building energy performance and post-occupancy evaluation. However, other areas, such as RM remain relatively unexplored. This research aims to identify BIM and IoT solutions applied to FM and propose a framework of BIM IoT uses assessed against associated gains, losses, enablers and barriers to implementation. A Systematic Literature Review (SLR) of journal and conference articles published between 2013 and 2018 was carried out to identify the outputs of BIM and IoT implementation for RM services. The review shows that the number of relevant articles is increasing and that there is also a lack of clarity regarding the cost-benefit of IoT. While the benefits and gains of systems are emphasized, disadvantages must be investigated. This research also revealed that there is a significant amount of uncertainty regarding guidance for the adoption of combined BIM and IoT applied to the improvement of RM services provision.

Keywords: Building Information Modelling (BIM), Internet of Things (IoT), Facilities Management (FM), Reactive Maintenance (RM)

1. Introduction

We crave efficiency in our businesses and yet fail to pay attention to the many areas that enable increased efficiency such as FM. Buildings can be too hot, too cold, too damp, or have high levels of CO2 concentration impacting staff performance. Poor maintenance can prevent the use of built assets, thus, driving staff out of offices, requiring clients to be relocated, and cancelling planned operations. The cost of fixing building problems is often a compounded of construction costs, reputational damages, service penalties and litigation costs. Firms also pay the price for not looking after facilities adequately, for not reacting quickly enough, and for not preventing problems before they occur. Although the desired alignment between business and FM has been continuously evolving as a reflection of improving information technology and communication systems effectiveness, there is still much to do. Early research such as Abel et al. (2006) and Atkin & Brooks (2009) showed that information modelling enables the coordination of FM processes that are essential for business operations while providing crucial information to facilities managers and corporate decision makers.

Building Information Modelling (BIM) is increasingly being investigated as a solution for increased efficiency in FM provision (e.g. Hosseini et al., 2018; Pärn, Edwards, & Sing, 2017; Patacas et al., 2016; Pin, Medina & MCarthur, 2018; Volk, Stengel, & Schultmann, 2014). There is evidence that information modelling is a powerful approach to aid facilities managers to improve building performance, to manage hard and soft operations more efficiently throughout the life cycle of buildings, and to enable circular economies. The amount of information about the real use of BIM for building operation and maintenance is growing with large public owners finally embracing and benefiting from BIM. However, much still needs to be understood. Advancements in areas such as IoT and Machine Learning has increased the number of potential uses of BIM in FM as well as the levels of efficiency that are possible to be achieved. Thus, a Systematic Literature Review (SLR) was carried out to aiming to gather and structure state-of-the-art knowledge about BIM and IoT implementation as an aid to FM. Special attention was paid to BIM and IoT for reactive maintenance (RM). From the analysis, a framework for the classification of research is proposed that identifies: research fields, FM priority areas, strategic FM operations and the benefits of and barriers to adoption. This framework should enable the establishment of a business case for BIM and IoT adoption.

2. Material and Methods

A SLR was carried out following the guidelines suggested by Gough et al. (2012). SLR generates subject context through the systematic identification, compilation, analysis and synthesis of reliable studies (Gough et al., 2012). It also ensures bias exemption (or, at least, its minimization) and increases the replicability of reviews (Morandi & Camargo, 2015). Also, it helps with establishing a picture of the transformations of a subject over a studied period while supporting decisions on future research paths and the use of research knowledge in practice. In this research, a research protocol was devised that led to the development of a conceptual framework used for data analysis. The SLR was divided into four steps, including research protocol development, searching, selection and extraction; as explained in the following sections.

3. Review Steps and findings

3.1 Systematic Review Entries

Table 1 provides an overview of the input criteria utilised as a part of the research protocol. Of twelve databases considered initially, seven were selected due to the availability of publications in the field of BIM and FM. Keywords and relevant Boolean Operators are presented in Table 1. The term “reactive maintenance” (RM) was excluded, so to broaden the search scope and to avoid the exclusion of relevant articles that use different terminology when referring to RM. Both peer-reviewed journal and conference articles were considered eligible publications. The research focused on recent innovative solutions; thus, only articles published between 2013 and 2018 were included.

Table 1: Research protocol

Item	**Content**
Research questions	What are the BIM and IoT solutions and devices recently applied to FM? In which areas and activities have these solutions been used? What are the main benefits, gains, enablers and barriers of this implementation?
Key objectives	To establish contextual knowledge regarding the implementation of BIM and IoT solutions on FM through the search, analysis and classification of articles and conference articles published between 2013 and 2018.
Databases	1. Scopus, 2. Technology Collection (ProQuest), 3. Science Direct (Elsevier), 4. Directory of Open Access Journals, 5. ASCE Library, 6. Compendex (Engineering Village) and 7. Web of Science (Web of Knowledge).
Keywords	("Building Information Modeling" OR "Building Information Modelling" OR BIM) ("Facilities Management" OR "Facility Management" OR FM) AND ("Internet of things" OR IoT)
Filters	Year of publication: 2013 to 2018. Type of publication: peer-reviewed journal and

	conference articles. Idiom: English, Portuguese, Spanish, Italian
Selection criteria	Inclusion criteria: articles investigating the implementation of BIM and IoT solutions in FM. Exclusion criteria: Publications that were not related to BIM and IoT for FM; outside the investigated research area; not written in the determined idioms.

In total, 273 publications were initially identified from journal articles, conference proceedings and PhD theses. After applying inclusion and exclusion criteria, 49 publications were selected for further analysis. Data was extracted through full-text review and publications classified according to title, authorship, type of publication, publication year, source (journal or conference), country, keywords, and three key areas: BIM and IoT solutions and devices, FM areas and activities, and positive and negative results obtained. Additional nine publications were excluded from the selection as they failed to meet protocol criteria. Figure 1 shows the distribution of publications per database throughout the different searching stages and the predominance of Scopus, Technology Collection, Science Direct and Compendex for the final 40 publications selected.

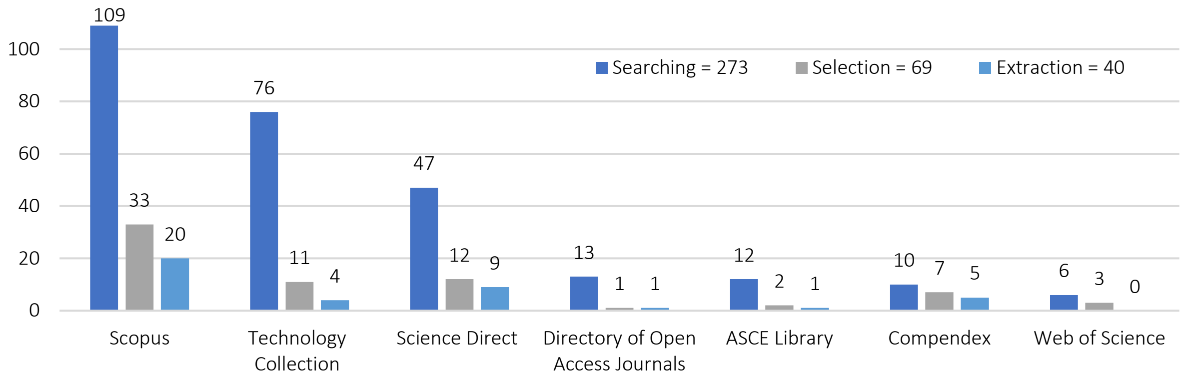
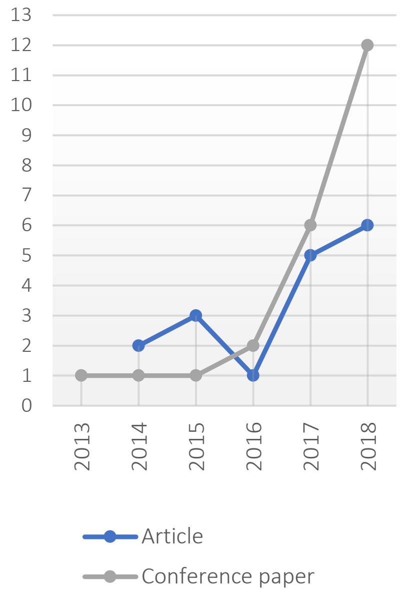


Fig. 1. Distribution of publications per database

3.2 General bibliometric analysis

The bibliometric analysis shows that 17 peer-reviewed journal articles and 23 conference articles were included and that there has been a steady increase in publications per year (Figure 2) since 2013. Figure 3 shows that contribution comes from 22 countries, thus revealing that although various countries started studying the subject, the critical mass is still embryonic (various countries with 1 or 2 publications). There is a predominance of articles (25) originated within, or with the participation of, European countries. The existence of bias is possible due to the use of English and Latin languages within the search. There is a concentration of publications in Italy (5), China (4), Taiwan (3) and the United Kingdom (3). Also, five articles spanned more than one country, evidencing a degree of international collaboration and knowledge sharing on this subject.

The distribution of publications according to where they were published shows 13 journals and 20 conferences. *Procedia Engineering*, *Advanced Engineering Informatics* and *Automation in Construction* have the highest concentration, accounting for approximately 47% of the articles (e.g. Costa et al., 2015; Kučera & Pitner, 2018), thus placing BIM and IoT for FM research within general engineering sources. No trend was identified for conferences, but there is a concentration of articles in events related to Automation and Robotics in Construction (5) (e.g. Chung et al., 2018; Lee et al., 2017) and IoT Technologies (3) (e.g. Pouke et al., 2018; and Ramprasad et al., 2018), which indicates that BIM and IoT for FM research refers to applied research.



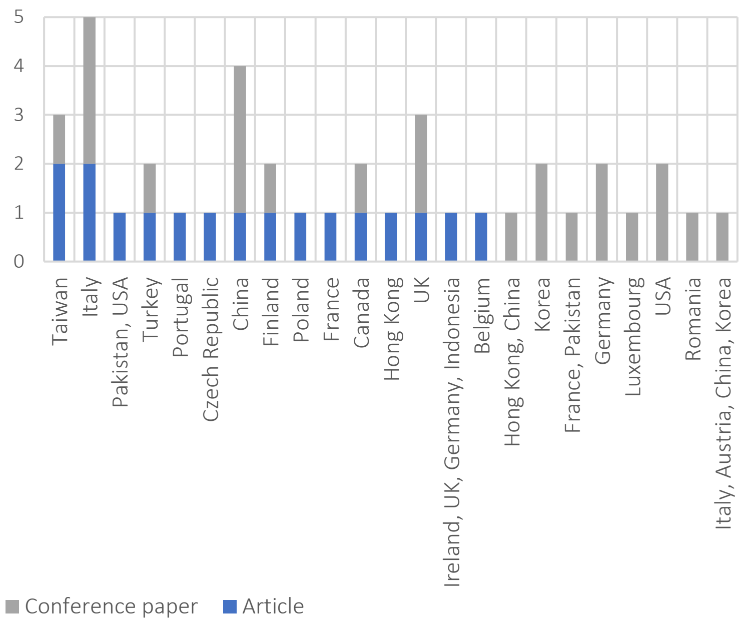


Fig. 2. Distributions of publications per year

Fig. 3. Distribution of publications per country

3.3 BIM and IoT core areas of research

With regards to core research areas, the analysed articles revealed three approaches being used for the integration of BIM and IoT for FM.

1) Process (17 entries) including the development of conceptual frameworks, methods and models for BIM-FM and IoT integration (e.g. Chen et al., 2015; Gokceli et al., 2017);

2) Technology (20 entries) including platform, software, system or tool for the integration of BIM and IoT technologies and interoperability of data related to FM (e.g. Arslan et al., 2017; Marroquin et al., 2018);

3) Theory (3 entries) including theory testing and theory generation for the integration of information and communications technology (ICT) or the description of previous applications of these technologies on BIM-FM and IoT (e.g. Araszkiewicz, 2017; Hanley & Brake, 2017).

Only articles that tested concepts through illustrative, prototype and pilot studies followed by real implementation were included in categories 1 and 2. Table 2 provides a summary of the results with examples to illustrate the three approaches. The following section covers the analysis of the 40 articles included, focusing on the technological aspects of BIM and IoT and its impact on FM and particularly on RM.

Table 2. FM BIM IoT Research core area, implementation and examples

Core area	Implementation	Example
1. Process: frameworks, methods and models for BIM and IoT integration	Illustrative, prototype or pilot implementation (9)	"A smart maintenance work process applicable to smart FM systems" (Chung et al., 2018)
	Real case implementation (6)	"A theoretical framework for digital systems integration of virtual models and smart technologies" (Mirarchi et al., 2018)
	No implementation (2)	"Realtime facility management system framework based on BIM and Web of Things" (Lee et al., 2013)

2. Technology: platforms, software, systems and tool for BIM and IoT integration	Illustrative, prototype or pilot implementation (14)	"BeDIPS - Building/environment Data-based Indoor Positioning System" (Liu et al., 2015)
	Real case implementation (6)	"3i buildings Systems - Intelligent, Interactive, and Immersive Buildings Systems" (Costa et al., 2015)
3. Theory	No implementation (3)	"Cup-of-Water theory" (Ye et al., 2018)

3.4 BIM and IoT solutions and devices for FM

With regards to IoT sensing devices, five key technologies are explicitly applied to FM activities independently or in combination. Out of 51 technologies mentioned, 73% are sensors and actuators (e.g. Dave et al., 2018; Gunduz et al., 2017), including, for example, Bluetooth Low Energy (BLE) beacons, general sensors for measuring temperature, humidity, CO2, lighting, occupancy and virtual sensors (added as an object within the 3D model of the facility); For RM, sensors are integrated into an indoor location system to identify users' position when reporting a failure (Mirarchi et al., 2018); 14% are Radio-frequency identification (RFID) tags and readers (e.g. Motamedi et al., 2016); 4% are smart cameras (e.g. Marroquin et al., 2018) and 4% are Quick Response (QR) codes used in RM for the acquisition and tracking of maintenance information (Lin et al., 2014). Finally, 5% of the articles were not sufficiently clear to fit within one of the above categories; one example is the "Smart field BIM-FM technology proposed by Chung et al. (2018) to support maintenance work on site.

Seven categories were proposed to classify solutions for BIM and the integration of data from sensing devices in FM: software application, system and network application; cloud and database solution; availability of building system; mobile application; smart devices; and associated technologies (Table 3). The results show a concentration of *Autodesk* software solutions, described in 19 publications, including 1 journal article describing the use of software for capturing and storing facility maintenance information to support RM, such as maintenance records and interface reports (Lin et al., 2014); other software solutions have been utilized less often, such as Unity software (3) and Trimble Tekla Structures (1). Building Management Systems (BMS) are present in 6 articles, followed by Building Automation Systems (BAS) in 4 publications. Nine articles applied user-friendly mobile applications, including the *Aalto Space*, *HereUAre* and *Nextome Noovle,* used in RM for end-users and FM staff registering and localising faults and monitoring service attendance (Mirarchi et al., 2018). Smartphones are mentioned in 10 publications within the smart device category, followed by Arduino in 3 publications. General smart devices are described in 5 articles, including webcam-enabled tablet and notebook supporting maintenance activities, such as fault location via QR code reading, visualisation of records information, monitoring service status and generation of reports (Lin et al., 2014).

Other FM associated technologies found include Blockchain for data security; Machine learning for automation of energy consumption data collection, processing and generation; photogrammetry and laser scanning associated with Geographic Information System (GIS) and Global Positioning System (GPS) for data digitalisation. Particularly applied to RM were Virtual Reality (VR) and Augmented Reality (AR) support site positioning and the visualisation of real-time facility information during maintenance inspections (Chung et al., 2018).

Table 3. FM BIM and IoT solutions

Item	Main BIM and IoT solutions and examples of publications
Software	Autodesk software (Revit, Revit Architecture, Dynamo, Green Building Studio, 3D Max, Autocad) (e.g. Lin et al. (2014); Unity Game Engine (e.g. Louis & Rashid, 2018); Trimble Tekla Structures (Costin et al., 2014)
System	Wireless Sensor Networks (WSN) (e.g. Ph.D & Ye, 2018); Integrated

and network	Workplace Management System (IWMS) (e.g. Hanley & Brake, 2017); IoT Watson IBM (Ciribini et al., 2017); Near-field communications (NFC) (Araszkiewicz, 2017)
Cloud and database	Microsoft SQL Server (Gerrish, Ruikar, Cook, Johnson, & Philip, 2018), IoT Platform Azure (Teizer et al., 2017), MS Access database (Costin et al., 2014)
Building system	Building Management System (BMS) (Gokceli et al., 2017), Building Automation System (BAS) (Kučera & Pitner, 2018)
Mobile application	Aalto Space mobile application (Dave et al., 2018; Kubler et al., 2016), HereUAre (Liu et al., 2015), Nextome Noovle mobile apps (Mirarchi et al., 2018)
Smart devices	Smartphone (e.g. Vandecasteele et al., 2017), Arduino (e.g. Chang et al., 2018), Tablet and Notebook (e.g. Lin et al., 2014), Wearable devices (e.g. Desogus et al., 2017)
Associated Technologies	Blockchain (Ye et al., 2018), Virtual Reality (VR) and Augmented Reality (AR) (Chung et al., 2018), Machine learning (McGlinn et al., 2017), Aerial photogrammetry (Edmondson et al., 2018), Geographic Information System (GIS) (Ronzino et al., 2015), Global Positioning System (GPS) (Ph.D & Ye, 2018)

3.5 FM areas, activities and applications

Figure 4 presents the classification and occurrence of the publications according to the FM areas and activities as described by Barrett and Finch (2014). Because some publications combined more than one area and activity, the total number of occurrences is higher than the number of analysed articles. Building operations and maintenance is the most investigated FM area with 84 entries, followed by general/office services (12) and facility planning (10). With regards to FM activities, the five most relevant are: Monitoring performance (26), running and maintaining plant (18), voice and data communication (16), health and safety (12) and energy management (14) where emphasis has been placed upon predictive actions related to energy consumption optimisation rather than corrective ones.

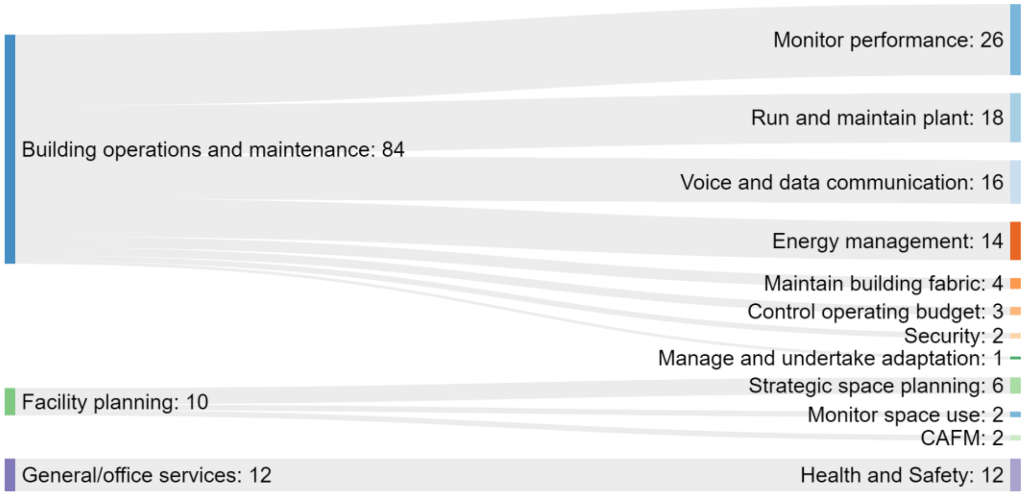


Fig. 4. Classification and occurrence of FM areas and activities

Key applications and examples found are summarised in Figure 5. These include building data management and synchronization (9) (e.g. Ramprasad et al., 2018), environmental monitoring and compliance checking (7) (e.g. Terkaj et al., 2017), energy and environmental management, monitoring and visualization (5) (e.g. Chang et al., 2018), operational and maintenance management (4) (e.g. Desogus et al., 2017) and location tracking (3) (e.g. Costin et al., 2014). Only three publications clearly describe applications relating to Maintenance Work as a process, from which two are related to Reactive Maintenance (correction, inspection and repair) (Lin et al., 2014; Mirarchi et al., 2018).

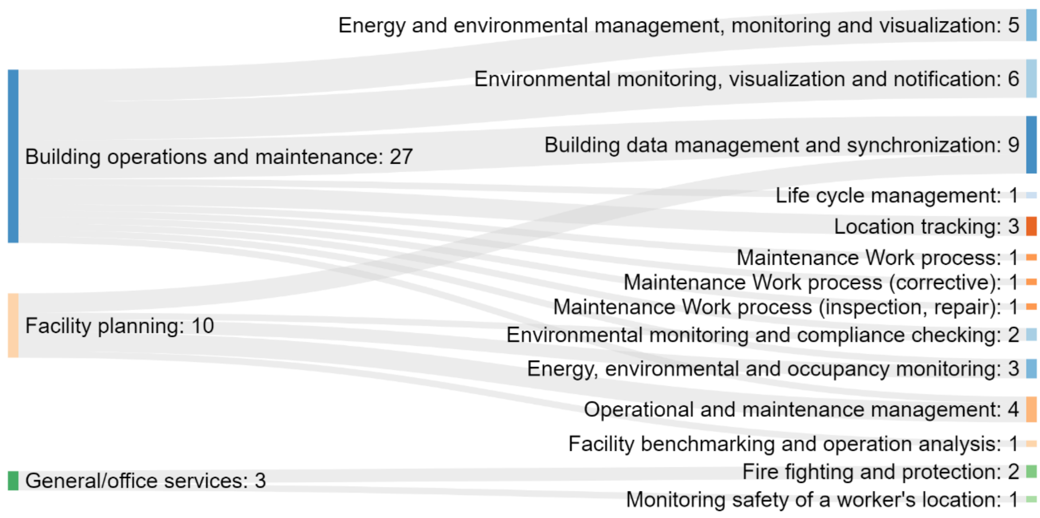


Fig. 5. Classification and occurrence of FM areas and applications of BIM and IoT

3.6 Outputs of BIM and IoT implementation for FM

Selected publications generated a total of 112 entries related to BIM and IoT implementation for FM according to its' measured and potential benefits (60), gains (32), enablers (5) and barriers (15). These were grouped into seven subcategories (Figure 6): increase or decrease of user's health & safety, comfort and satisfaction, technological issues, increase or decrease of FM efficiency, productivity and financial issues, occurrence of ethical and user privacy issues, increased or decreased environmental sustainability, enhanced (shared) building data management and asset planning, management and operation. No losses resulting from the adoption of BIM-FM and IoT were reported within the selected publications, thus revealing positive bias within the research. This aspect is depicted in Figure 6, showing that positive outputs are represented more often than negative ones. Readers must consider, however, that negative results tend not to be published due to risks associated with reputational damage as it occurs in POE studies.

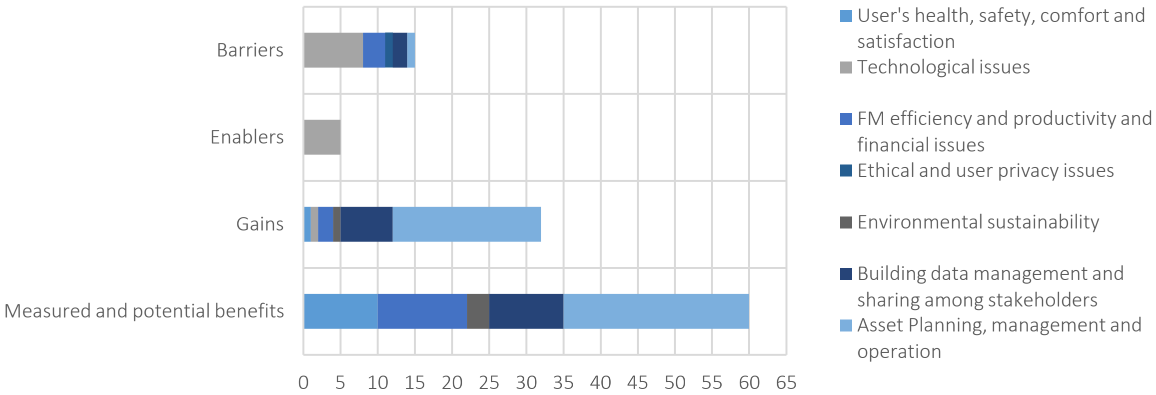


Fig. 6. Distribution of BIM and IoT implementation outputs for FM per publication

In relation to identified benefits, articles mostly describe the potential impact of the combined technologies on asset planning management and operations (25) followed by FM efficiency and productivity and financial issues (12). General examples within this category include "anticipating users' needs to support decision-making for retrofit projects" (Desogus et al., 2017); and "AEC/FM digitalisation high efficiency and security" (Ye et al., 2018), while for RM the benefits are "in facilitating FM updates and transfers in the BIM environment" (e.g. Lin et al., 2014) and "the management of the whole cycle of maintenance activities using a unique integrated system" (e.g. Mirarchi et al., 2018).

As expected, the main gains relate to asset planning, management and operation (20) and building data management and sharing (10). For example, instant information about problems supporting facilities managers in rapid fault detection (Desogus et al., 2017); availability of “a complete management system”, including historical data and current condition, enabling verifications on the behaviour of buildings (Di Giuda et al., 2018). Technology is a key enabler for BIM and IoT implementation for FM in 5 entries. For RM, Lin et al. (2014) highlight the low cost of QR code labels in comparison to RFID technologies; Ciribini et al. (2017) explore machine learning and IoT. In their research, sensors generate real-time human activity data that informs adaptive and predictive strategies embedded in BMS systems which makes automatic changes in environmental controllers (e.g. light levels and temperature control) for improved users’ comfort and service attendance. Technology is also seen as the core barrier for BIM and IoT based services (8), followed by FM efficiency and productivity and financial issues (3). Examples include: “trade-offs between interoperability problems within existing sensor systems and high costs related to the development of simplified and integrated systems” (e.g. Arslan et al., 2014); the “large volume of inaccessible and incoherent information gathered through sensors” (e.g. Desogus et al., 2017). For RM, examples include reported difficulties for new user to operate the BIM model in the BIFM system; the fragility of QR code labels to external environmental pollution (Lin et al., 2014); and the limited precision of location system (Mirarchi et al., 2018).

3.7 Conceptual framework of BIM IoT implementation for FMRM

The conceptual framework presented in Figure 7 synthesises the key aspects for the investigation of BIM and IoT implementation for FM/RM. The areas within the framework are the classification of FM areas and activities; definition of an approach for BIM and IoT integration; characterisation of the structure for combining BIM and IoT solutions and devices; and identification of the outputs of BIM and IoT implementation.

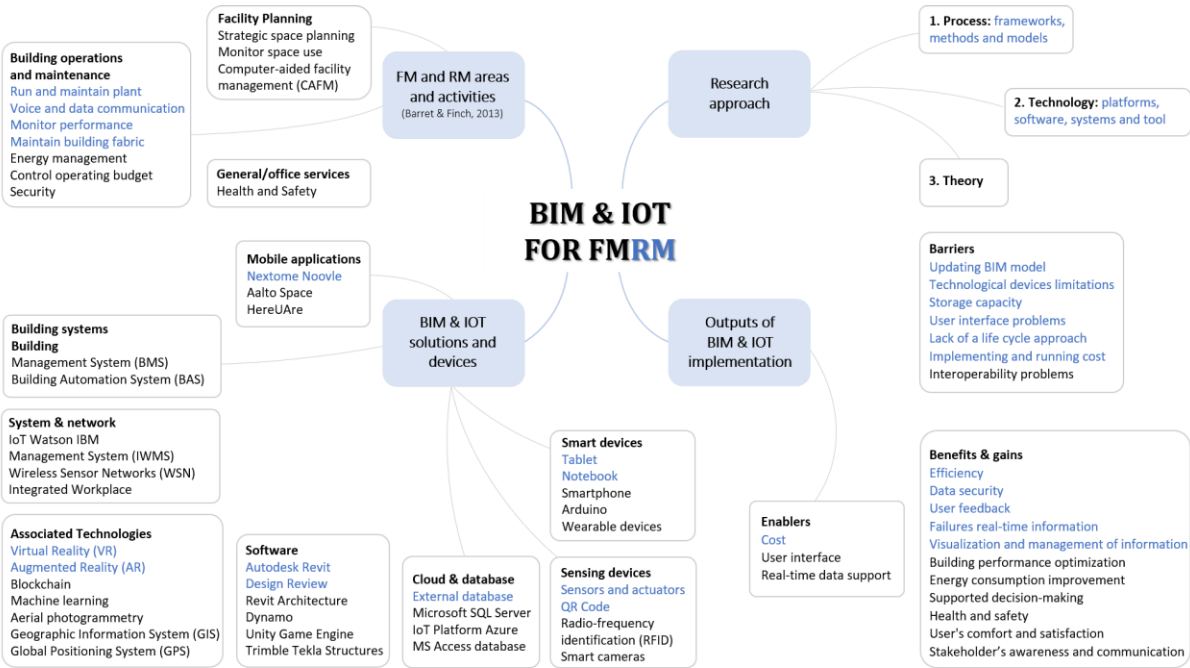


Fig. 7. Framework for BIM and IoT implementation for FMRM

4. Discussion

This work evidences the scarcity of studies in the field during the investigated period. The predominance of publications from European countries stored in three databases highlights the concentration of the topic in specific scientific environments. The prevalence of studies proposing conceptual processes and technological tools for BIM and IoT integration evidences the novelty of the theme and the need for advances in storing, exchanging and integrating building operation data, establishing a background for further implementation. Moreover, most of those constructs were validated through pilot implementations, highlighting, on one hand, the interest in developing applicable solutions, while on the other hand, illustrating the demand for implementations in real cases as a strategy for measuring tangible effects over the efficiency FM activities. As shown in Figure 3, although the publications were less representative between 2013 and 2016, we can observe an increasing trend after that, particularly in conference articles, which totalled twice the number of articles in 2018.

As summarised in Table 3, the solutions for building information modelling involve many components beyond sensing devices and software, which makes for even more complex BIM and IoT combined implementation. For FM activities, in general, there is a prevalence of sensors and RFID tags and readers, Autodesk software, smartphones, mobile applications and associated technologies (e.g. VR, AR). Although no trend is verified for RM in the small sample analysed, there is the potential for adapting general solutions to these activities, respecting inherent limitations highlighted by some authors (Chung et al., 2018; Lin et al., 2014; Mirarchi et al., 2018).

The predominance of publications about building operations and maintenance, particularly for monitoring building performance, managing energy consumption and voice and data communication shows that BIM and IoT based FM plays a key role in enhancing FM activities during the life cycle of a building. It provides intelligent data and solutions for enhancing the Operation and Maintenance (O&M) stage, and also to feedback and integrate designers and contractors in the early stages of the design process. However, the availability of only two RM related articles evidences the lack of studies in this area, disregarding its impact on service provision, user satisfaction and business value.

The measured and potential benefits and gains are the most significant outputs of BIM and IoT implementation for FM. In general, and for RM, the emphasis has been on the integration of building information in a centralized database, the availability of real-time updated information, the improvement of the quality and management of information among stakeholders, the fast response to faults and the performance of buildings over the lifespan. Technology is both the main enabler for BIM and IoT implementation due to its capability to process real-time information and to propose alternatives for improving user comfort and service attendance and as the main barrier as the cost and complexity of collecting, storing and exchanging interoperable building data are still major challenges. There is an evident bias towards technology-related research.

Regards to BIM/IoT/RM-based services, this article has identified different approaches to improve the communication and management of asset information. Mirarchi et al. (2018) develop a system for asset traceability, damage detection and reporting and communication of failures, based on indoor location technologies (i.e. GIS and mobile application), integrated to FM BIM models. The focus is on tracking users' position as one reference for locating the reported problems and linking this information to the BIM model. Although faults' precise location requires being interpreted by the facility manager according to other sources of information (e.g. photos, descriptions), the system provides an easy interface for users, FM staff and the supply chain actively participating in the RM process, improving the efficiency of the service. A mobile system for inspection and maintenance work was also proposed by Lin et al. (2014), integrating asset information captured through 2D barcode technology to FM BIM models. In their research, the emphasis was placed on FM staff acquiring and tracking asset information directly from the labelled elements of the building, improving the information sharing and the RM services efficiency. With distinct levels of end-user involvement, both solutions face the challenge to overcome the technological limitations and to structure the modelling, transference and update of information among IoT, FM and BIM systems, thus requiring further investigations.

Holistic approaches, covering not only the technical challenges in the FM process but also people issues and the changing business models driving FM, such as the circular economy and how we are now learning from information related to the whole life cycle of existing buildings in design of new buildings, did not appear in this systematic literature review. Although the positive outputs outweigh the negative ones, it is necessary to deeply investigate all the barriers and then propose strategies to mitigate their impact on BIM and IoT applications for FM, optimising the use of resources and seeking affordable devices and solutions for each situation. Also, it is essential to map RM processes in more detail in order to identify which services and activities can be potentially improved through BIM and IoT implementation. More research is needed to fill this gap.

5. Conclusion

Through an SLR, this work establishes a context for the implementation of BIM and IoT solutions in FM between 2013 and 2018. Addressing the research questions, BIM and IoT devices and solutions recently applied to FM, and particularly to RM, were identified, as well as the main FM areas, activities and applications. Finally, the outputs of this implementation were examined, highlighting benefits, gains and enablers rather than barriers and losses. The work indicates that RM activities represent a small field of investigation, providing a range of opportunities for new approaches and applications. The research shows that the number of articles is increasing and that there is a lack of clarity regarding the cost-benefit of BIM and IoT combined implementation. The categories and strategies for developing this work are summarised in the proposed conceptual framework which, along with the findings, contribute to understand the subject and to support future studies.

One of the limitations of this study was the difficulty of tracking publications within the databases due to the multidisciplinary nature of the subject, crossing engineering and computer science fields. Also, the focus on articles is based on secondary sources of data, providing a synthesis of previous investigations. In this respect, further research supported by empirical evidence (e.g. case studies, surveys, interviews) is recommended in order to provide metrics around costs and the impacts of BIM and IoT implementation for FM, particularly for RM. These and future studies are necessary to strengthening FM's key role in improving building life-cycle efficiency and the AEC industry.

Acknowledgements

The authors would like to acknowledge the financial support by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) Grant No. 88881.188668/2018-01, FAPESP (São Paulo Research Foundation) Grant No. 2019/05640-4 and CNPQ (National Council for Scientific and Technological Development) Grant No. 306998/2018-1.

References

Abel, J., Diez, K. & Lennerts, K. (2006). A Standard Database Model for Computer Aided Facility Management in Hospitals. *Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, 535–542.

Araszkiewicz, K. (2017). Digital Technologies in Facility Management - The state of Practice and Research Challenges. In *Procedia Engineering* (Vol. 196, pp. 1034–1042). The Author(s). https://doi.org/10.1016/j.proeng.2017.08.059

Arslan, M., Riaz, Z., Kiani, A. K., & Azhar, S. (2014). Real-time environmental monitoring, visualization and notification system for construction H&S management. *Journal of Information Technology in Construction, 19*(June), 72–91. Retrieved from https://www.itcon.org/papers/2014_4.content.05036.pdf

Arslan, M., Riaz, Z., & Munawar, S. (2017). Building Information Modeling (BIM) Enabled Facilities management using hadoop architecture. In *PICMET 2017 - Portland International Conference on Management of Engineering and Technology: Technology Management for the Interconnected World, Proceedings* (Vol. 9-13 July, pp. 1–6). Portland, OR, USA. https://doi.org/10.23919/PICMET.2017.8125462

Atkin, B., & Brooks, A. (2009). *Total Facilities Management. Facilities* (Third). John Wiley & Sons Ltd. https://doi.org/A John Wiley & Sons, Ltd., Publication

Barrett, P., & Finch, E. (2014). *Facilities management : the dynamics of excellence* (Third). Chichester: John Wiley & Sons Ltd.

Chang, K., Dzeng, R., & Wu, Y.-J. (2018). An Automated IoT Visualization BIM Platform for Decision Support in Facilities Management. *Applied Sciences*, *8*(7), 1086. https://doi.org/10.3390/app8071086

Chen, K., Lu, W., Peng, Y., Rowlinson, S., & Huang, G. Q. (2015). Bridging BIM and building: From a literature review to an integrated conceptual framework. *International Journal of Project Management, 33*(6), 1405–1416. https://doi.org/10.1016/j.ijproman.2015.03.006

Chung, S., Kwon, S., Moon, D., & Ko, T. (2018). Smart Facility Management Systems Utilizing Open BIM and Augmented/Virtual Reality. In *35th International Symposium on Automation and Robotics in Construction (ISARC)* (p. 8). https://doi.org/10.22260/isarc2018/0118

Ciribini, A. L. C., Pasini, D., Tagliabue, L. C., Manfren, M., Daniotti, B., Rinaldi, S., & De Angelis, E. (2017). Tracking Users' Behaviors through Real-time Information in BIMs: Workflow for Interconnection in the Brescia Smart Campus Demonstrator. *Procedia Engineering, 180,* 1484–1494. https://doi.org/10.1016/j.proeng.2017.04.311

Costa, A. A., Lopes, P. M., Antunes, A., Cabral, I., Grilo, A., & Rodrigues, F. M. (2015). 3I Buildings: Intelligent, Interactive and Immersive Buildings. *Procedia Engineering*, *123*(123), 7–14. https://doi.org/10.1016/j.proeng.2015.10.051

Costin, A., Pradhananga, N., & Teizer, J. (2014). Passive RFID and BIM for Real-time Visualization and Location Tracking (pp. 169–178). https://doi.org/10.1061/9780784413517.018

Dave, B., Buda, A., Nurminen, A., & Främling, K. (2018). A framework for integrating BIM and IoT through open standards. *Automation in Construction*, *95*(August 2017), 35–45. https://doi.org/10.1016/j.autcon.2018.07.022

Desogus, G., Quaquero, E., Sanna, A., Gatto, G., Tagliabue, L. C., Rinaldi, S., … Villa, V. (2017). Preliminary performance monitoring plan for energy retrofit: A cognitive building: The 'Mandolesi Pavillon' at the University of Cagliari. In *2017 AEIT International Annual Conference: Infrastructures for Energy and ICT: Opportunities for Fostering Innovation, AEIT 2017*. https://doi.org/10.23919/AEIT.2017.8240529

Di Giuda, G. M., Villa, V., Tagliabue, L. C., Giana, P. E., Rinaldi, S., & Ciribini, A. L. C. (2018). Refurbishment and school buildings management in a smart building environment. In *AIP Conference Proceedings* (Vol. 1968). https://doi.org/10.1063/1.5039257

Edmondson, V., Cerny, M., Lim, M., Gledson, B., Lockley, S., & Woodward, J. (2018). A smart sewer asset information model to enable an 'Internet of Things' for operational wastewater management. *Automation in Construction, 91*, 193–205. https://doi.org/10.1016/j.autcon.2018.03.003

Gerrish, T., Ruikar, K., Cook, M., Johnson, M., & Philip, M. (2018). Visual pattern recognition as a means to optimising building performance? In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. https://doi.org/10.1007/978-3-319-91635-4_31

Gokceli, S., Zhmurov, N., Kurt, G. K., & Ors, B. (2017). IoT in Action: Design and Implementation of a Building Evacuation Service. *Journal of Computer Networks and Communications*, *2017*, 1–13. https://doi.org/10.1155/2017/8595404

Gough, D., Oliver, S., & Thomas, J. (2012). *SYSTEMATIC REVIEWS* (1st ed.). London: SAGE.

Gunduz, M., Isikdag, U., & Basaraner, M. (2017). INTEGRATION of BIM, WEB MAPS and IOT for SUPPORTING COMFORT ANALYSIS. In *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* (Vol. 4, pp. 221–227). https://doi.org/10.5194/isprs-annals-IV-4-W4-221-2017

Hanley, B. P., & Brake, D. J. (2017). Putting asset data at the heart of organisational decision-making using an Integrated Workplace Management System (pp. 32 (7 .)-32 (7 .)). https://doi.org/10.1049/cp.2016.1432

Hosseini, M. R., Roelvink, R., Papadonikolaki, E., Edwards, D. J., & Pärn, E. (2018). Integrating BIM into facility management. *International Journal of Building Pathology and Adaptation*, *36*(1), 2–14. https://doi.org/10.1108/IJBPA-08-2017-0034

Kubler, S., Buda, A., Robert, J., Främling, K., & Traon, Y. Le. (2016). Building lifecycle management system for enhanced closed loop collaboration. In *IFIP Advances in Information and Communication Technology*. https://doi.org/10.1007/978-3-319-54660-5_38

Kučera, A., & Pitner, T. (2018). Semantic BMS: Allowing usage of building automation data in facility benchmarking. *Advanced Engineering Informatics*, *35*(January 2017), 69–84. https://doi.org/10.1016/j.aei.2018.01.002

Lee, S., Kim, S., Oh, E.-H., Shin, E.-Y., Kang, T.-K., & Lee, Y.-S. (2017). Realtime Facility Management System Framework Based on Building Information Modeling and Web of Things. In *Proceedings of the 30th International Symposium on Automation and Robotics in Construction and Mining (ISARC 2013): Building the Future in Automation and Robotics*. https://doi.org/10.22260/isarc2013/0144

Lin, Y.-C., Su, Y.-C., & Chen, Y.-P. (2014). Developing mobile BIM/2D barcode-based automated facility management system. *Scientific World Journal*, *2014*, 16. https://doi.org/10.1155/2014/374735

Liu, J. W. S., Chen, L. J., Su, J., Li, C. C., & Chu, E. T. H. (2015). A Building/Environment Data Based Indoor Positioning Service. In *Proceedings - 2015 IEEE International Conference on Data Science and Data Intensive Systems; 8th IEEE International Conference Cyber, Physical and Social Computing; 11th IEEE International Conference on Green Computing and Communications and 8th IEEE Inte* (pp. 505–512). https://doi.org/10.1109/DSDIS.2015.46

Louis, J., & Rashid, K. (2018). Utilizing building information models as operating systems for smart homes. In *Human-habitat for Health Workshop (H3'18) ACM International Conference on Multimodal Interaction (ICMI'18)* (pp. 1–4). https://doi.org/10.1145/3279963.3281658

Marroquin, R., Dubois, J., & Nicolle, C. (2018). Ontology for a Panoptes Building: Exploiting Contextual Information and a Smart Camera Network. *Semantic Web*, *9*(September), 803–828. https://doi.org/10.3233/SW-180298

McGlinn, K., Yuce, B., Wicaksono, H., Howell, S., & Rezgui, Y. (2017). Usability evaluation of a web-based tool for supporting holistic building energy management. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2017.08.033

Mirarchi, C., Pavan, A., De Marco, F., Wang, X., & Song, Y. (2018). Supporting Facility Management Processes through End-Users' Integration and Coordinated BIM-GIS Technologies. *ISPRS International Journal of Geo-Information*, *7*(5), 191. https://doi.org/10.3390/ijgi7050191

Morandi, M. I. W. M., & Camargo, L. F. R. (2015). Revisão sistemática da literatura. In *DRESCH, A.; LACERDA, D. P.; ANTUNES JÚNIOR, J. A. V. Design Science Research - método de pesquisa para avanço da ciência e tecnologia.* (pp. 141–172). Porto Alegre: Bookman.

Motamedi, A., Soltani, M. M., Setayeshgar, S., & Hammad, A. (2016). Extending IFC to incorporate information of RFID tags attached to building elements. *Advanced Engineering Informatics*, *30*(1), 39–53. https://doi.org/10.1016/j.aei.2015.11.004

Neges, M., Wolf, M., Propach, M., Teizer, J., & Abramovici, M. (2017). Improving Indoor Location Tracking Quality for Construction and Facility Management. In *Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC)*.

https://doi.org/10.22260/isarc2017/0012

Pärn, E. A., Edwards, D. J., & Sing, M. C. P. (2017). The building information modelling trajectory in facilities management: A review. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2016.12.003

Patacas, J., Dawood, N., Greenwood, D., & Kassem, M. (2016). Supporting building owners and facility managers in the validation and visualisation of asset information models (aim) through open standards and open technologies. *Journal of Information Technology in Construction*.

Ph.D, C. H., & Ye, H. (2018). A Novel IoT-Cloud-BIM Based Intelligent Information Management System in Building Industrialization. In *International Conference on Construction and Real Estate Management 2018* (pp. 72–77). Charleston, South Carolina. https://doi.org/https://doi.org/10.1061/9780784481721.008

Pin, C., Medina, C., & McArthur, J. J. (2018). Supporting Post-Occupant Evaluation Through Work Order Evaluation and Visualization in FM-BIM. In *Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC)*. https://doi.org/10.22260/isarc2018/0005

Pouke, M., Virtanen, J. P., Badri, M., & Ojala, T. (2018). Comparison of two workflows for Web-based 3D smart home visualizations. In *2018 IEEE International Conference on Future IoT Technologies, Future IoT 2018* (Vol. 2018-Janua, pp. 1–8). https://doi.org/10.1109/FIOT.2018.8325599

Ramprasad, B., Mcarthur, J., Fokaefs, M., Barna, C., Damm, M., & Litoiu, M. (2018). Leveraging existing sensor networks as IoT devices for smart buildings. In *IEEE World Forum on Internet of Things, WF-IoT 2018 - Proceedings* (Vol. 2018-Janua, pp. 452–457). IEEE. https://doi.org/10.1109/WF-IoT.2018.8355121

Ronzino, A., Osello, A., Patti, E., Bottaccioli, L., Danna, C., Lingua, A., … Rasconà, G. (2015). The energy efficiency management at urban scale by means of integrated modelling. *Energy Procedia*, *83*, 258–268. https://doi.org/10.1016/j.egypro.2015.12.180

Sava, G. N., Pluteanu, S., Tanasiev, V., Patrascu, R., & Necula, H. (2018). Integration of BIM Solutions and IoT in Smart Houses. In *Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018* (pp. 1–4). IEEE. https://doi.org/10.1109/EEEIC.2018.8494628

Teizer, J., Wolf, M., Golovina, O., Perschewski, M., Propach, M., Neges, M., & König, M. (2017). Internet of Things (IoT) for Integrating Environmental and Localization Data in Building Information Modeling (BIM). In *Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC)*. https://doi.org/10.22260/isarc2017/0084

Terkaj, W., Schneider, G. F., & Pauwels, P. (2017). Reusing domain ontologies in linked building data: The case of building automation and control. In *CEUR Workshop Proceedings* (Vol. 2050).

Vandecasteele, F., Merci, B., & Verstockt, S. (2017). Fireground location understanding by semantic linking of visual objects and building information models. *Fire Safety Journal*, *91*(February), 1026–1034. https://doi.org/10.1016/j.firesaf.2017.03.083

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction*, *38*, 109–127. https://doi.org/10.1016/J.AUTCON.2013.10.023

Ye, Z., Yin, M., Tang, L., & Jiang, H. (2018). Cup-of-Water Theory: A Review on the Interaction of BIM, IoT and Blockchain During the Whole Building Lifecycle. In *Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC)*.

https://doi.org/10.22260/isarc2018/0066

Zhong, B., Gan, C., Luo, H., & Xing, X. (2018). Ontology-based framework for building environmental monitoring and compliance checking under BIM environment. *Building and Environment, 141*(May), 127–142. https://doi.org/10.1016/j.buildenv.2018.05.046

Interactive Holographic Scenes for Teaching Wireless Sensing in Construction Engineering and Management

Abiola Akanmu[1*] and Johnson Olayiwola[2]
[1,2] Myers Lawson School of Construction, Virginia Tech, Blacksburg, VA, USA
* email: abiola@vt.edu

Abstract

The proliferation of ubiquitous technologies coupled with the demands for delivering safer, less intrusive and more resilient building and civil infrastructure projects are pushing modern construction industries into investing in various types of sensing technologies such as laser scanners, drones, radio frequency identification systems and global positioning systems. Sadly, there is a shortfall of graduating construction engineering and management engineers or existing workforce equipped with the required knowledge and skills for developing and implementing sustainable solutions to the nation's infrastructure issues with these technologies. To prepare students for this future of construction, a few number of university engineering and construction programs have begun offering courses that include sensing technology content. However, owing to the hands-on learning requirement of the technologies, students have limited access to construction sites to collaboratively try-out or examine the potentials of these sensing systems in addressing project risks. These experiences are usually difficult to provide because of the hazardous nature of construction sites and constraints such as limited access, schedule, and weather. One approach to providing this experience is to project interactive platforms, in the form of holographic scenes and objects, a concept of mixed reality, of construction sites into the classroom environment, so that students can explore strategies for implementing sensing technologies. Using these augmented three-dimensional objects, students can visualize and interact with digital representations of construction sites and sensing technologies in the physical classroom environment. Students can feel present on construction site environments by enabling them to move naturally and explore in three dimensions, the spatial distribution, boundaries, dependencies and interaction between tasks. This paper presents the development of the interactive holographic scenes and objects, and preliminary studies exploring the extent to which this pedagogical tool can be used to provide students with a learning environment that enables them to gain hands-on experience with the use of the sensing technologies. A descriptive account of how the interactive holographic scenes can be used to provide hands-on experience in an educational environment is provided.

Keywords: Augmented Reality, Sensing, Holographic Scenes, Education and Construction

1. Introduction

Over the past five years, the rate of adoption of sensing technologies in the construction industry has grown exponentially (Dixon, Connaughton, & Green, 2018). There have been multiple reports of how construction companies are deploying sensing systems for tracking real-time performance and physical states of construction workers (Ball, 2016; Group, 2008; Team, 2014). Specifically, there has also been increasing reports of the use of vision-based systems (e.g. drones and laser scanners) for site inspection, work measurement and safety management. This advancement and diffusion of sensing systems in the construction industry, has triggered the demand for candidates/workforce with computing skills. However, there is a shortfall of graduating construction engineering and management (CEM) engineers equipped with the required knowledge and skills for developing and implementing sustainable solutions with sensing technologies. Some of the inhibitors to equipping CEM students with these competencies are: (a) limited access to construction sites where students can collaboratively try-out different sensing systems; and (b) owing to the cost of these technologies, some institutions struggle to provide experience and training to the students. These and similar challenges have prompted increased interest in the exploration of virtual resources for creating analogous learning environments where students can explore the potentials of sensing technologies.

In recent years, there has been an increased interest in the exploration of virtual environments for classroom instruction (Dib & Adamo-Villani, 2013), conducting experiments and interactive simulations (Alexander, Brunyé, Sidman, & Weil, 2005; Goulding, Nadim, Petridis, & Alshawi, 2012; Li, Chan, & Skitmore, 2012). Virtual environments have been known to enhance cognitive learning in engineering education (Balamuralithara & Woods, 2009; Ieronutti & Chittaro, 2007; Kollöffel & de Jong, 2013; Nikolic, Jaruhar, & Messner, 2011; Sampaio, Henriques, & Martins, 2010). By projecting interactive platforms (in the form of holograms and holographic scenes, a concept of augmented and mixed reality) of construction sites into the classroom environment, students can explore strategies for implementing the technologies for developing solutions to industry problems. In the context of this study, holographic scenes refer to augmented reality that appears to the user as holograms or three dimensional (3D) objects existing in the physical world. Using these augmented 3D objects in the form of holograms (Fig. 1), students can visualize and interact with digital representations of construction sites and sensing technologies in the physical classroom environment. Students can feel present on construction site environments by enabling them to move naturally and explore in three dimensions, the spatial distribution, boundaries, dependencies and interaction between tasks. In addition, students can perform selective analysis of construction tasks, operations and resources. Using the HoloLens, a head mounted display popularized by Microsoft, the holograms are produced in the form of AR that appear as 3D objects existing in the physical space. These holograms respond to gaze, gestures and voice commands. With the HoloLens, construction sites can be projected in front of a student or group of students (Fig. 1); they can touch and tag resources (e.g. equipment), position sensors (e.g. laser scanners, drones and real-time location sensors) and observe ergonomic exposures of construction workers. Furthermore, students can collaboratively navigate a construction site and within buildings to observe indoor and outdoor activities, with each student having different points of view.

Hence, this paper presents findings of an ongoing research aimed at creating and assessing a pedagogical framework based on holographic scenes for equipping CEM students with the competencies required for deploying data sensing technologies on construction projects. This paper describes the theoretical framework guiding the development of the interactive holographic scenes. The development and a descriptive account of the implementation of the interactive holographic scenes is presented.

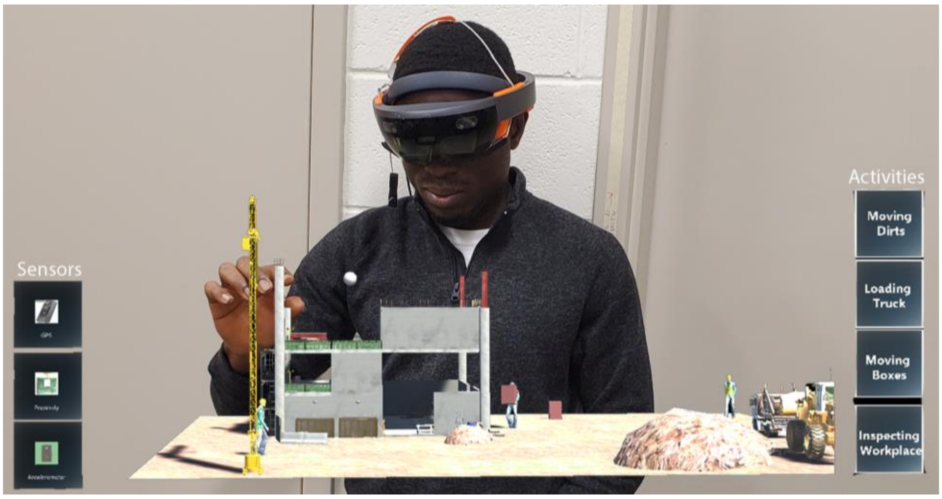


Figure 1: Example of a Hologram

2. Background

The potential of AR technologies in educational practices is recently gaining attraction. Cuendet, Bonnard, Do-Lenh, Dillenbourg, and Education (2013) designed an AR tool for classroom instruction. The authors demonstrated the adequacy of the tool for enhancing learning and engagement in the classroom. Kaufmann, Schmalstieg, Wagner, and technologies (2000) created a 3D construction tool using an immersive AR environment. The tool allows student and instructors to construct geometric shapes with head-mounted displays. Behzadan and Kamat (2013) developed a learning tool to enable students interact with remote construction job sites in the classroom. With the aid of the tool, students were able to view and retrieve relevant information regarding an object of interest from a video of a job site. Fjeld, Juchli, and Voegtli (2003) designed an augmented chemistry application which helps in teaching abstract organic chemistry concepts. To help engineering students develop spatial skills Martín-Gutiérrez et al. (2010) designed an augmented book which the students can use to visualize virtual objects. Despite the benefit of these technologies, the navigability of these tools is limited to the size and position of the markers. In addition to the fact that existing studies have not explored the applications of AR to the use of sensing systems, there have also been limited opportunities to truly explore interactivity of the AR environment – this is critical for promoting constructive learning. Although, holographic tools have been around for a while, there has been limited exploration of this technologies for enhancing engagement and learning. Some of the few notable studies include the following: In the medical industry, (Tres3D) developed a tool that enables students to view 3D holographic medical animations. Lee (2013) argued the use of 3D holographic technology for testing operations of real-world systems. Liarokapis et al. (2004) identified that integrating holographic technology with interactivity can provide students with learning experiences that are otherwise difficult to obtain. By surveying over 400 teachers in the United Kingdom, Ghuloum (2010) concluded that the holographic technology can function as an effective teaching and learning tool. With the advent of technologies such as the HoloLens capable of projecting interactive augmented 3D objects as holograms, opportunities exist to apply this concept to CEM education. Specifically, the ability to project interactive construction sites into the classroom environment can enhance situated and constructed learning experiences.

3. Theoretical framework and appropriate pedagogies for AR learning experience

The basis for employing AR for enhanced learning experiences is grounded in situated and constructivist learning theories. Situated and constructivist learning are purposefully been used to understand learning, knowing and doing as context-specific social processes by characterizing cognition as being socially shared (Lave, Wenger, & Wenger, 1991; Moore & Rocklin, 1998). These notions are rooted in both Vygotskian's understandings of higher mental processes as internalized social relationships (Newman & Holzman, 2006) and Dewey's early objections to stimulus-response theory (Clartcey, 2008). Because both situated, and constructivism hold many similarities, this study synergistically used both as framework to guide the development of the interactive holographic scenes. Using situated cognition and constructivism, strategies can be formulated for situating students' project work within an AR context, rich with its own material, social and educational dimensions. These project works are usually structured to involve real-life activities and challenges. Through learning from the process, also known as an experiential learning, students "take ownership" of the development of their new skills and knowledge (Kolb, 2014), by being actively involved in the process, reflecting and conceptualizing, and using new ideas gained from the experience for problem solving and decision making (Dewey, 1938). By including interactive platforms in the form of holographic scenes and objects of construction sites into the classroom environment, there will be more opportunities for student-centered active learning. In an effort to provide experiential learning experience, situated in real-life practices to all CEM students in the classroom, pedagogies of engagement will demand "project in context" AR learning scenario to provide students with authentic industry experiences and opportunities to reflect and conceptualize on what they learn. By utilizing project in the context of an

AR learning environment, the interactive holographic scene promises to reduce student's learning barriers with construction concepts and implementation of sensing systems.

4. Holographic Learning Environment

The main objective of designing the interactive holographic scene is to create environments that will enable students, through manipulation, to develop skills for problem/risk identification on construction projects and evaluate different sensing options/strategies for addressing the risks. The holographic learning environment shown in Fig. 2, provides a platform for students to explore the following: (1) investigate the characteristics of the jobsite; (2) selectively isolate the activities to investigate the suitability of different sensing systems; (3) implement the sensing systems; and (4) perform a cost-benefit analysis of the selected sensing solutions. The system architecture of the developed holographic learning environment is shown in Fig. 3. In general, the key elements of the module include development of animated GameObjects via Unity3D and holograms via the HoloLens. These are described as follows:

4.1 Animated GameObjects

Unity3D consists of GameObjects, services, and the Mixed Reality Toolkit (MRTK). Their functions are described as follows:

- *GameObjects:* The GameObjects are the construction site environment, resources, buttons and sensors. The site environment contains a partially completed building and temporary structures. The resources include construction workers, equipment (tower crane, trucks and loaders) and some materials. The buttons serve as control or initiation points for the activities, resources and sensors. With the sensor buttons, students can tag resources with the global positioning system (GPS), inertia measurement unit, radio frequency identification system, and proximity sensors. The activities button enables students to initiate construction tasks such as hauling materials and site inspection. With the resources button, students can select appropriate resources for implementing the tasks such as a truck, loader, material or laborer. Each of the button contains scripts that trigger specific behaviors when they are clicked on. When students gaze at any of these buttons, they are able to use the air-tap hand-based gesture in the HoloLens to select the button. For example, on clicking on the GPS tag, students are able to tag any of the outdoor construction resources. If a student gazes on and air taps any of the activity buttons, the gaming environment will isolate the selected activity and grey out other construction activities buttons. Furthermore, the resources associated with the activity will be displayed beside the clicked button. On selecting any of the resources, the resource will be tagged with the GPS tag.

  Each of the game objects have interactive components such as the animator, playable director and mesh collider. With these interactive components, animations were created for the game objects. The animator was used to generate individual animation clips for each game object e.g. a laborer carrying out lifting tasks or the trucks hauling materials. With the animator, movements were assigned to the GameObjects such as translation and rotation within the construction site. The playable director uses the animator component to assign the recorded animations to the GameObjects. The mesh collider component was added to enable interaction between students and the GameObjects.
- *Services:* The services are used for improving user experience while using the HoloLens. The game module uses the graphics device services to determine the appropriate graphics application programming interface to reduce and balance the load on the Holographic Processing Unit.
- *Mixed Reality Toolkit:* The MRTK is a third-party library package consisting of the cursor, the HoloLens camera, and gaze control. The gaze control uses the position and orientation of a learner's head to determine their gaze vector. The gaze control uses the cursor to shoot a laser into the students view or on any of the GameObjects. This gives learner's confidence in what

they are trying to interact with. Unlike traditional computer screen which displays 3D content on 2D screen, the HoloLens camera projects the GameObjects as holograms.

4.2 GameObjects as Holograms

To be able to view the animated GameObjects as holograms via the HoloLens, the developed game is loaded into the Microsoft HoloLens via the Holographic Remote application in Unity3D. To use this application, HoloLens is connected to the internet and the application is built using the Visual Studio Universal Windows Platform. On connecting the HoloLens to the internet, the Holographic Emulation uses the HoloLens Wi-Fi internet protocol address to stream the animated GameObjects from Unity3D. As the students interact with the holographic environment, their movements are captured and translated into a first-person avatar.

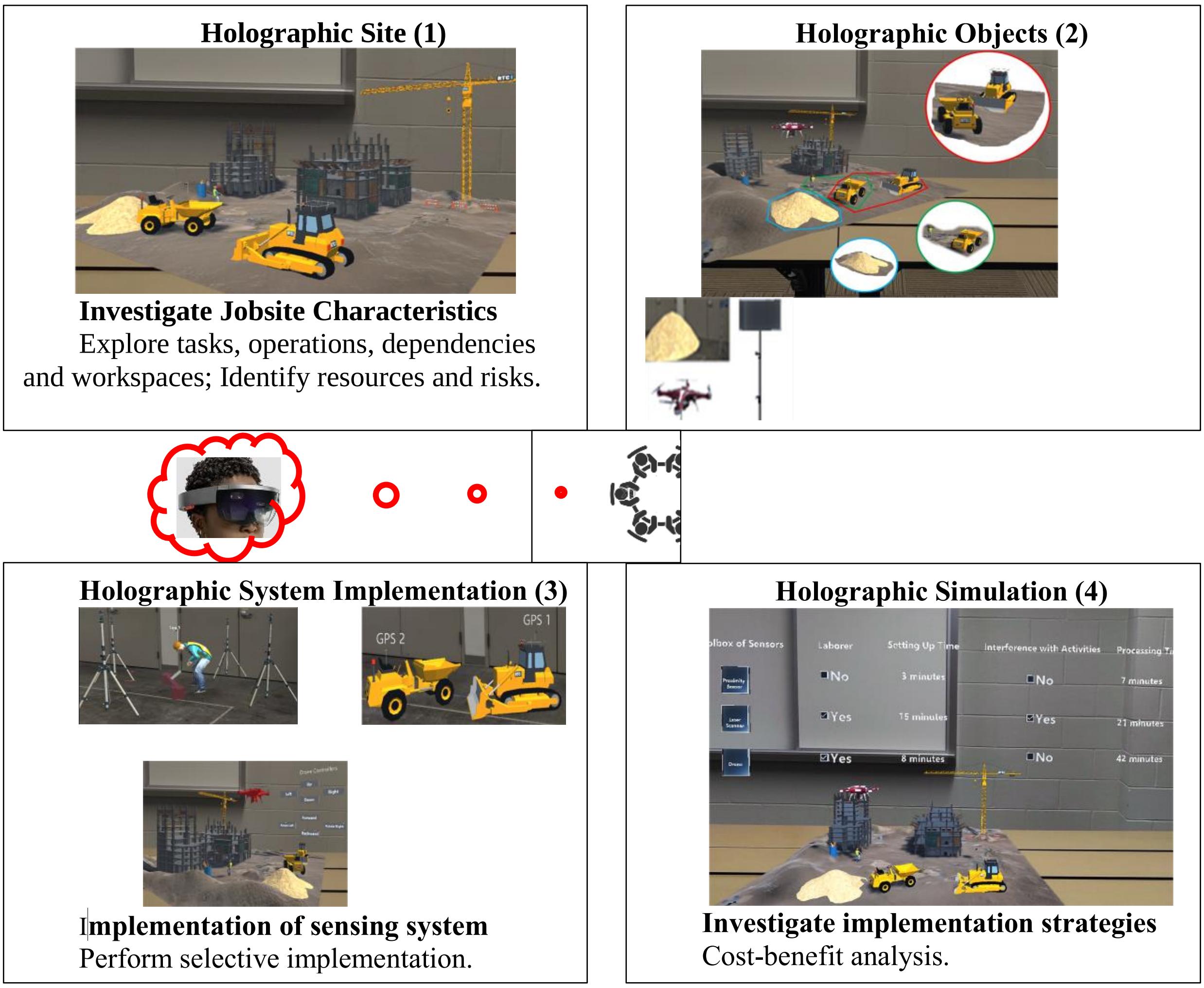


Figure 2: Holographic Environment for Learning Sensing Systems

5. Implementation and Preliminary Results

The working prototype provides a platform for facilitating classroom instruction and student project work. Students can interact with the virtual construction activities in the holographic learning environment. The learning activities in the holographic scenes are formulated based on realistic scenarios of construction activities. Students are able to work collaboratively by navigating the scenes to perform the following: (1) distinguish between construction activities; (2) identify dependencies and interaction between the resources; (3) define workspaces of activities; (4) identify potential risks (from each activity) to project performance; (5) select and try-out different sensing systems for addressing the project risks; (6) observe the data structures from each sensing system, and (7) determine suitable formats for presenting solutions for quick decision making. Depending on the selected activities, choice of sensing systems and placements, the holographic environment will show the suitability or appropriateness of the sensing plan for addressing the intended problems.

Using the HoloLens, which can project 3D augmented objects as holograms, students can easily navigate construction sites, isolate activities to observe the workings of resources, and implement different sensing technologies such as the real-time location sensors (Fig. 4a), IMU (Fig. 4b), laser scanner (Fig. 4c) and drones (Fig. 4d). Presently, only the GPS, IMU and proximity sensor objects are functional in the preliminary prototype. The preliminary prototype can be used to instruct students on how to use sensing systems for addressing construction related issues such as assessing ergonomic risks of workers, tracking productivity, identifying potential near-misses and close calls. For example, for construction ergonomics, students can select a task e.g., 'Moving Materials' task and the worker assigned to carry out this task is isolated in the game. A table of body parts which are usually prone to ergonomic risks (B. o. L. S. (BLS), 2018) for the worker are displayed and the student can select any of the body parts. For example, for a painter, the head, back, shoulder and lower arm are the subject to the greatest ergonomic risk (B. o. L. a. S. (BLS), 2016). The back is annotated to show the angle of bent from the neutral plane or standing position as shown in Fig. 4b. A postural ergonomic risk classification table as shown in Table 1 is displayed to the student (Chander & Cavatorta, 2017). This will help students form a mental image of the physical demand of construction work, how the body angles are measured, and the relationship between the angles and the risk.

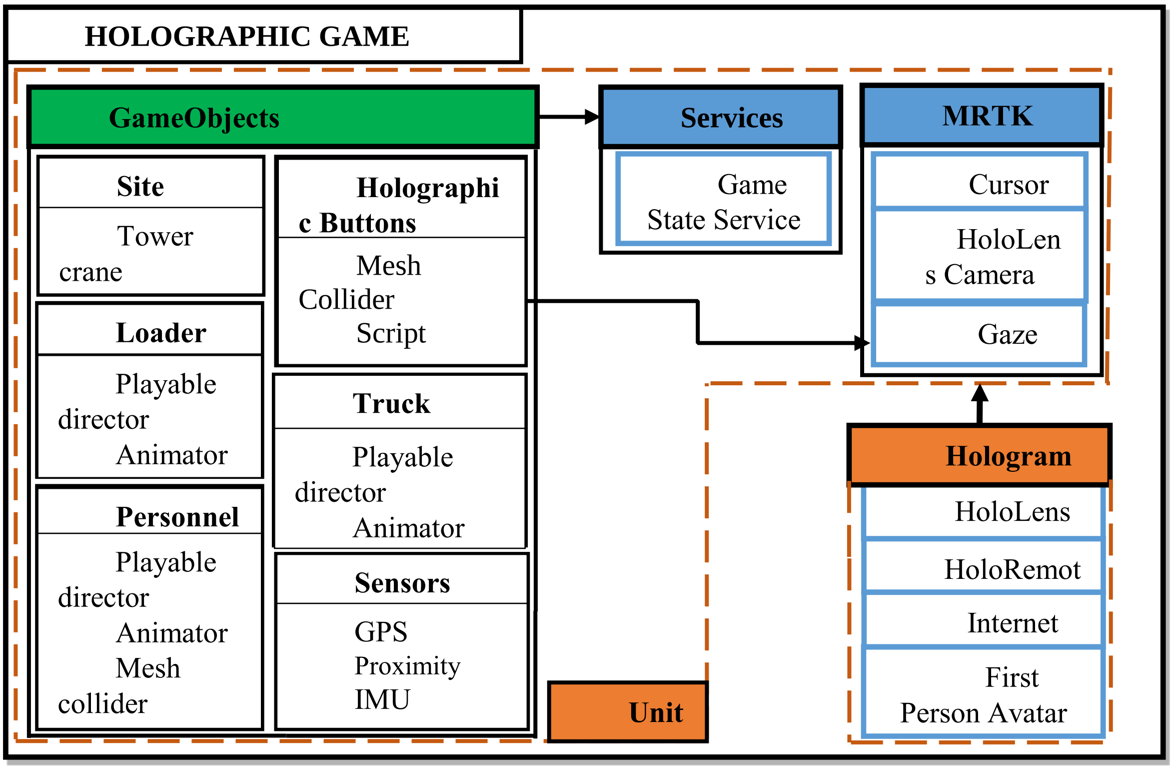
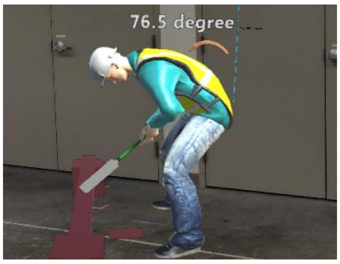
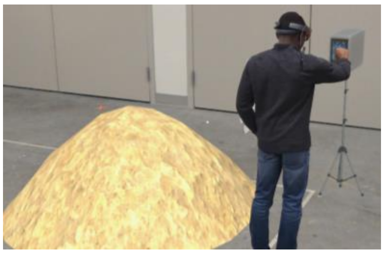


Figure 3: System Architecture of Holographic Learning Environment

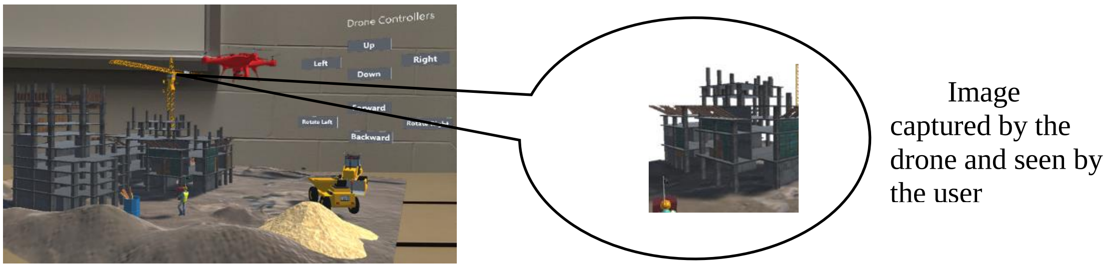
(a) RFID-RTLS tagged worker



(b) IMU tagged worker



(c) Scanning stockpile



(d) Drone surveying site

Figure 4: Preliminary Proof of Concept of Holographic Scenes

Table 1: Risk Classification Chart

Body Part	No Risk	Low Risk	Medium Risk	High Risk
Trunk Flexion		0 – 20	21 – 60	>60
Trunk Lateral Flexion			0 – 10	>10
Shoulder Flexion		0 – 20	21 – 60	>60
Elbow Flexion		0 – 20	21 – 60	>60
Hip Flexion	0 – 30	31 – 60	61 – 90	>90

6. Conclusions and Future Work

As construction companies continue to adopt sensing systems, it is important to equip the future CEM workforce with the competencies required for utilizing these systems. Limited accessibility to jobsites and cost of these technologies are some of the factors that currently limits opportunities to provide these learning experiences to students. This paper presents the development of an interactive virtual construction environment in the form of holographic scenes, where students can closely observe construction activities, understand how to identify possible risks and investigate suitability of different sensing systems for addressing the risks. The holographic scenes consist of animated GameObjects which can be viewed and manipulated as holograms via the HoloLens. With the HoloLens, students can navigate, interact, and visualize the projected holographic scenes. The preliminary prototype currently includes functional GPS, IMU and proximity sensors. The prototype also enables productivity and safety assessments of construction activities. As part of future work, the GameObjects of the sensing systems shown in Figs. 4a, 4b, 4c and 4d will made functional. Usability studies will be conducted to improve the functionality of the prototype.

References

(BLS), B. o. L. a. S. (2016). Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work. Retrieved from https://www.bls.gov/news.release/pdf/osh2.pdf

(BLS), B. o. L. S. (2018). *Nonfatal Occupational Injuries and Illnesses in the Construction Industry*. Retrieved from https://data.bls.gov/pdq/SurveyOutputServlet

Alexander, A. L., Brunyé, T., Sidman, J., & Weil, S. A. (2005). From gaming to training: A review of studies on fidelity, immersion, presence, and buy-in and their effects on transfer in pc-based simulations and games. *DARWARS Training Impact Group, 5*, 1-14.

Balamuralithara, B., & Woods, P. C. (2009). Virtual laboratories in engineering education: The simulation lab and remote lab. *Computer Applications in Engineering Education, 17*(1), 108-118.

Ball, M. (2016). Turner Construction Uses Drones to Monitor Construction at Sacramento Kings New Arena. Retrieved from http://informedinfrastructure.com/20656/sacramento-kings-new-arena-incorporates-drone-monitoring-system/

Behzadan, A. H., & Kamat, V. R. (2013). Enabling discovery-based learning in construction using telepresent augmented reality. *Automation in Construction, 33*, 3-10.

Chander, D. S., & Cavatorta, M. P. (2017). An observational method for postural ergonomic risk assessment (PERA). *International journal of industrial ergonomics, 57*, 32-41.

Clartcey, W. J. J. T. C. h. o. s. c. (2008). Scientific antecedents of situated cognition. 11.

Cuendet, S., Bonnard, Q., Do-Lenh, S., Dillenbourg, P. (2013). Designing augmented reality for the classroom. *Computers & Education, 68*, 557-569.

Dewey, J. (1938). Experience and education: the Kappa Delta Phi lecture series. *New York, NY: Kappa Delta Pi*.

Dib, H., & Adamo-Villani, N. (2013). Serious sustainability challenge game to promote teaching and learning of building sustainability. *Journal of Computing in Civil Engineering, 28*(5), A4014007.

Dixon, T., Connaughton, J., & Green, S. (2018). Understanding and Shaping Sustainable Futures in the Built Environment to 2050. *Sustainable Futures in the Built Environment to 2050: A Foresight Approach to Construction and Development*, 337.

Fjeld, M., Juchli, P., & Voegtli, B. M. (2003). *Chemistry education: a tangible interaction approach.* Paper presented at the Proc. INTERACT.

Ghuloum, H. (2010). *3D hologram technology in learning environment.* Paper presented at the Informing Science & IT Education Conference.

Goulding, J., Nadim, W., Petridis, P., & Alshawi, M. (2012). Construction industry offsite production: A virtual reality interactive training environment prototype. *Advanced Engineering Informatics, 26*(1), 103-116.

Group, H. C. (2008). *Use of RFID in the Meadowlands Stadium Project*. Retrieved from https://www.bizjournals.com/sanantonio/news/2018/06/06/skanska-demos-construction-tech-being-tested-in.html
https://www.pci.org/PCI_Docs/Members_Only/Productivity%20Resources/Use%20of%20RFID%20in%20the%20Meadowlands%20Stadium%20Project.pdf

Ieronutti, L., & Chittaro, L. (2007). Employing virtual humans for education and training in X3D/VRML worlds. *Computers & Education, 49*(1), 93-109.

Kaufmann, H., Schmalstieg, D., Wagner, M. (2000). Construct3D: a virtual reality application for mathematics and geometry education. *Education and inofrmation technologies, 5*(4), 263-276.

Kolb, D. A. (2014). *Experiential learning: Experience as the source of learning and development*: FT press.

Kollöffel, B., & de Jong, T. (2013). Conceptual understanding of electrical circuits in secondary vocational engineering education: Combining traditional instruction with inquiry learning in a virtual lab. *Journal of engineering education, 102*(3), 375-393.

Lave, J., Wenger, E., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation* (Vol. 521423740): Cambridge university press Cambridge.

Lee, H. J. T. (2013). 3D holographic technology and its educational potential. *57*(4), 34-39.

Li, H., Chan, G., & Skitmore, M. (2012). Visualizing safety assessment by integrating the use of game technology. *Automation in Construction, 22*, 498-505.

Liarokapis, F., Mourkoussis, N., White, M., Darcy, J., Sifniotis, M., Petridis, P., … & Lister, P.F.(2004). Web3D and augmented reality to support engineering education. *World transactions on engineering and technology education, 3*(1), 11-14.

Martín-Gutiérrez, J., Saorín, J. L., Contero, M., Alcañiz, M., Pérez-López, D. C., Ortega, M. (2010). Design and validation of an augmented book for spatial abilities development in engineering students. *Computers & Graphics, 34*(1), 77-91.

Moore, J. L., & Rocklin, T. R. (1998). The distribution of distributed cognition: Multiple interpretations and uses. *Educational Psychology Review, 10*(1), 97-113.

Newman, F., & Holzman, L. (2006). *End Of Knowing*: Routledge.

Nikolic, D., Jaruhar, S., & Messner, J. I. (2011). Educational simulation in construction: Virtual construction simulator. *Journal of Computing in Civil Engineering, 25*(6), 421-429.

Sampaio, A. Z., Henriques, P. G., & Martins, O. P. (2010). Virtual reality technology used in civil engineering education. *The open virtual reality journal, 2*(1).

Team, H. (2014, 06.06.14). Importance of 3D Laser Scanning in Healthcare Renovations. Retrieved from https://www.hourigan.group/blog/importance-3d-laser-scanning-healthcare-renovations/

Tres3D. 3D Medical Animation |3D Medical Scientific Visualization | 3D Medical Animated | Medical Animation Studio. Retrieved from http://medical-animation-studio.com/index.php?mod=Static&id=home

The Role of Advanced Smart Sensors within Structural Health Monitoring: An Analysis of Case Studies from the United States

Iona Morrison* and Richard Laing
Robert Gordon University, Aberdeen, UK
* email: i.r.morrison1@rgu.ac.uk

Abstract

Urban settlements are under immense pressure to use the limited resources they have most effectively to manage advanced urbanisation. With the rising threat of potentially devastating natural disasters, such as earthquakes, city management is under enormous pressure to create urban development's which are robust, sustainable and adaptable to the consistently changing environment.

One such technology for future development is that of smart sensors. Smart sensors offer opportunities to deliver real-time, wireless, structural health monitoring (SHM) systems. Through the development of data management techniques, the information generated between the smart sensor networks can provide vital information for cities to monitor and control the structural integrity of urban infrastructure.

This research aimed to explore the role in which advanced smart sensor technologies play in monitoring structural health of critical infrastructure within the United States (U.S), with a focus within high-seismic areas, to aid in the understanding of the effectiveness of this emerging technology.

The methodology for this research called upon several approaches, including the review of smart sensor technologies based on a comprehensive qualitative case study analysis, together with literature review, and industry expert interviews. Case study reviews enabled the research to further elucidate the technical and practical implementation of SHM sensors within architectural technology to establish a vital role which smart sensors play within a practical SHM application.

The research concluded that there are a variety of commercially available sensor prototypes which could provide effective alternative solutions to traditional reactive visual inspections with real time, continuous structural monitoring. The integration of this technology within architecture holds the potential to transform relationships between building design and facilities management by extending the life of assets as well as improving the sustainability and resource challenges of cities.

The implementation of smart sensor technologies in urban architecture within high-seismic areas would ensure the right technology and communication systems are in place to warrant long-term planning and serviceability of structurally sound infrastructure. Nevertheless, the research recognised that realising the potential benefits will require further industry developments in innovative technologies and multi-disciplinary collaboration with regards to data collection and analysis. The research has identified an important line for research integrating architectural technology, smart technology, FM and data analytics. With this collaboration, continuous, real-time wireless SHM monitoring within high-seismic areas would ensure structural damage can be detected before reaching a critical state, producing robust and resilient architecture for extended lifecycle operation.

Keywords: Smart Sensors, Critical Review, Structural Health Monitoring, Internet of Things (IoT), Communication Technologies

1. Introduction

The potential exists in the world's cities for creating high quality and future proof infrastructure, dependent on urban development's being efficiently managed. Modern city infrastructure must be robust, resilient and adaptable to the consistently changing environment and omnipresent threats of catastrophic events presented by climate change. A total of 1808 earthquakes were recorded across the world in 2018 alone (USGS 2019) and with an estimated three-quarters of all deaths from earthquakes due to building collapse (Cross 2015), scientists warn a large increase in earthquakes in the coming years could cause tremendous tragedy. Figure 1 illustrates the rising occurrence of earthquakes over a magnitude of >3M in the United States of America (U.S); highlighting a significant increase of these natural disasters in previous years. Thus, it is critical that the right technology and skills are in place to ensure long-term planning for structurally sound and resilient urban infrastructure.

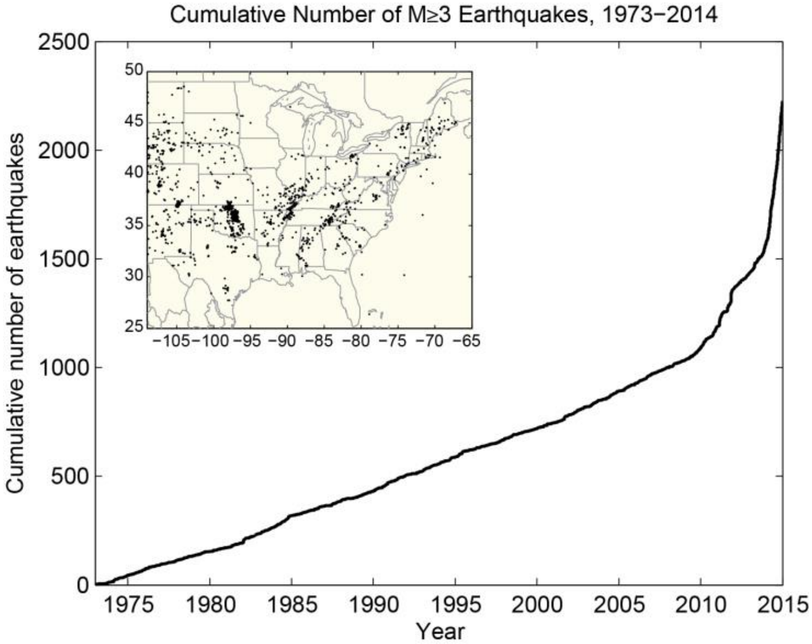


Figure 1: Cumulative number of earthquakes over magnitude of 3.0 in U.S (Jacobs 2015)

Additionally, with a rapid growth of urban populations it is predicated one out of every two now prefers to live within an urban environment, see figure 2 (Grover and Walia n.d), with an estimated 6 billion people living in urban areas by 2050 (Hancke, Silva and Hancke 2012). With this rapid pace of urbanisation, the necessity of high rise and multi-storey buildings has increased due to pressures to meet the needs of the growing urban population, producing some of the most dangerous constructions across the world. One precedent can be demonstrated in China, when in 2008 an earthquake destroyed over

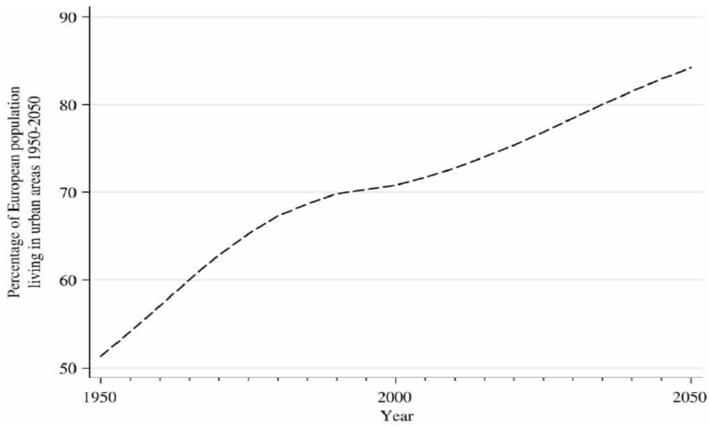


Figure 2: Rising populations in urban areas (Caraguli, Bo and Nijkamp 2011, fig 1, pp 65)

7000 school buildings which were constructed under inadequate building regulations in order to complete the project as quickly as possible to meet the increasing urban migration within the country

(Cross 2015). Thus, these poorly engineered structures resulted in major loss of life and resources.

This increasing migration puts a huge strain on the world's resources within urban areas, and with 3m sqf of office space currently under construction in downtown Los Angeles alone (Slowey 2019); it is vital to make cities greener and more sustainable. Buildings and cities can play a far more significant role in mitigating the use of resources than we might assume. To address these challenges, the vision for future urban developments is the design of 'Smart Cities'. Smart Cities use intelligent digital technology to promote performance as well as monitoring and controlling of its infrastructure to respond to global challenges (RICS 2017). One aspect within these cities would be the development of smart buildings. These would not only have the potential to drastically improve sustainability, but also to minimise the risk of structural deterioration within high-rise city buildings.

Smart sensing can be placed at the heart of smart buildings (Hancke et al 2013); with possible improvements enabled by sensing technologies being immense. Smart sensors have the potential to continuously monitor a structures technical condition through structural health monitoring (SHM) systems. SHM can fundamentally change the way critical urban infrastructure is maintained resulting in extension of lifecycle and more efficient use of resources (Klikowicz, Salamak and Poprawa 2016). Having the ability to monitor the integrity of structures in real-time can provide an awareness of possible structural damage, thus improving the safety of the public as well as improving reliability of the infrastructure during natural disasters such as earthquakes. It is hoped the result of this research will be valuable to the industry in providing a deeper understanding of the role and impact advanced smart sensors can have within the monitoring and reduction of deteriorating infrastructure in urban developments.

1.1 Aims and Objectives

The aim of this research was to develop an understanding of the role in which advanced smart sensor technologies play in providing structural health monitoring of high-rise buildings within high seismic areas. The key objectives were as follows:

- To develop an understanding of various advanced smart sensor technologies and their role in monitoring deteriorating infrastructure.
- To review current industry practical application of advanced sensor technology in improving structural integrity within urban infrastructure developments.
- To gain a deeper understanding of smart sensor data management and communication network operations.
- To outline constraints that might be faced within the practical application of advanced smart sensor technologies.

2. Material and Method

Within this study, three case studies were considered regarding various advanced smart sensor networks and applications within civil infrastructure in cities. Firstly, application of SHM sensors along the Alamosa Canyon Bridge were studied in order to evaluate the application of both wired and wireless accelerometer sensors. Further to this, a field validation test conducted on the Oakland Bay Bridge project within the U.S was considered. This established an in-depth level of knowledge regarding alternative smart sensor technology available. Finally, research was conducted on the application of advanced smart sensors within the high-rise Di Wang Tower. Analysis of this case study allowed for an efficient comparison between advanced smart sensor application in bridge structures and high-rise buildings.

The qualitative method within this research involved unstructured interviews with the aim of gaining a deeper understanding into the phenomenological approach to smart sensor technology to gain a deeper understanding of the practical application of advanced smart sensor technologies. In order to develop this strategy a range of professionals from a variety of industries were interviewed to critically discuss the themes which had been identified with regards to the previously analysed literature. These themes included: Sensor Parameters, Communication Networks, Data Management and Power Constraints. Industry experts included a business development manager for CENSIS, an industry-led innovation center for sensor and imaging technology; a senior computing lecturer with detailed knowledge within the IoT; a senior control room operator and a condition monitoring engineer within the oil and gas industry and lastly an experienced party wall surveyor with experience utilising smart sensors for vibration monitoring. Interviewees were asked a series of unstructured questions to allow open-ended comments, as illustrated in table 1 below.

Table 1: Unstructured Interview Question Guide

Number	*Question Guide*
1	What projects are you currently involved in which utilise smart sensor technologies?
2	What performance measurements were monitored? (eg. material strain, vibrations, traffic management, temperature?)
3	What type of sensors were used? (eg. accelerometers, piezoelectric, fibre optics?)
4	How were the sensors installed? (eg. Wired or wireless?)
5	Was specific training required to install the sensors?
6	How do the sensors communicate with each other? (eg. wifi, Bluetooth, open source?)
7	How do you secure and store the sensor data information? (eg. password protection? Cloud storage?)
8	Is there specialised training required to manage the data within a network management system?
9	Is there an alarm feature enabled for measured data reaching a certain threshold limit?
10	How are the sensors powered? (eg. Solar, Ethernet, battery?)
11	What were any constraints within the implementation of these sensors?

The results from the industry interviews, case study review and literature analysis established a vital role in which advanced smart sensor technology can play in SHM applications. A comparison of the full technical data of each sensor type analysed can be seen in table 2 below.

Table 2: Technical Data of Smart Sensor Technologies

	Crossbow CXL01LF1 MEMS Accelerometer	*Sensor Highway II F30a AcousticEmission (AE)*	*ADXL202 Acelerometer*
Parameter	2 axis acceleration and vibration sensor	Vibrations, cracks, fatigue	2 axis dynamic and static vibrations
Processing Platform	WiMMS	WiFi/Cellular	MICA Mote (Tiny OS)
Network (WPAN)	Proxim RangeLan2 (IEEE 802.11b)	WiFi (IEEE 802.11)	Linksys WAP11 (IEEE 802.1b)
Data Range	200kbps (137 – 304m)	Unavailable	11000kbps. (91 – 152m)
Installation	Retrofit	Retrofit Outdoors	Retrofit
Power Source	9V Battery	Phantom Power, Selectable 5V, 28V	3V to 5.25V Battery
Size	4’’ x 4’’ x 1.5’’	0.75’’x 0.85’’	0.4’’ x 0.4’’ x 0.2’’

2.1 Alamosa Canyon Bridge

The Alamosa Canyon Bridge was constructed in 1937 and is located in New Mexico (Farrar et al 2000) and demonstrates an excellent example in the utilisation of both wired and wireless sensor networks. Research conducted by Lynch et al (2003) measured ambient vibrations within the bridge which originated from continuous heavy traffic. To measure the dynamic response of the bridge to vibrations, two different accelerometers were installed upon the span's girder web: one wired and one wireless. The deployment of two different sensors types allowed information to be obtained for the comparison of tethered sensor technology to the more recent, less commercialised, wireless technology. In this field validation study, accelerometers were the primary sensor types implemented in order to measure the structural response of vibrations due to traffic loads.

The cable-based system employed was the Piezotronics PCB336C accelerometer. This sensor was chosen for the field validation test due to the high sensitivity and broad amplitude range it adopts. The installation of these sensors provided challenges in regard to the care and maintenance of the wires across the girders. Mounted adjacent to the cable based system was the Crossbow CXL01LF1 MEMS wireless accelerometers (Lynch et al 2003). Similar to the wired sensor system, the CXL01LF1 is a high sensitivity MEMS accelerometer with high-stability characteristics with a WiMMS processing platform and power supplied from 9V batteries.

To assess the effectiveness of both sensor networks deployed along the bridge, a sizable vibration test was conducted which employed an impact blow from a modal hammer as well as ambient vibration test produced by a large truck driving over the bridge.

2.2 San Francisco Oakland Bay Bridge

The San Francisco Oakland Bay Bridge (SFOBB) is one of the largest SHM research projects conducted by Mistras Group to date. When construction was completed in 1936, the bridge was named the longest spanning bridge in the world. Due to the location within such close proximity to two major fault lines within the U.S, the SFOBB was at risk of future catastrophic structural failures due to the seismic activity within the area, therefore providing an excellent test area for SHM applications.

Due to the busy traffic flow and limited maintenance access across the bridge, a system was required that could continuously monitor the structural integrity of the bridge, in real time, in order to prevent future collapse and structural deterioration over time. SHM through the use of smart sensor technology can represent an advantage over periodic visual inspections due to the improvements within public safety as well as real time monitoring; determining structural failures from miniscule cracks.

640 advanced smart acoustic emission (AE) sensors were deployed across 384 structural eye bars within the superstructure, mounted to the surface with a cyanoacrylate adhesive to provide an acoustic coupling between the sensor and the structure (Johnson et al 2012). AE techniques draw great attention to the analysis of fatigue and deformation within a material due to the immediate indication of materials under stress and damage. The role of advanced smart sensors presents the ability to detect significant cracks from initiation, with AE sensors detecting small bursts of energy emitted during crack initiation and growth. The sensors can be mounted within the structure in order to continually collect data within real time; ensuring any microscopic cracks in inaccessible areas are detected from as small as 0.1in.

2.3 Di Wang Tower

Within recent years there has been a clear necessity for an effective and economical method for managing the health of tall buildings throughout their lifespan as failure of such a structure would result in immediate fatal loss of life and economic loss. Even with the recent upsurge of attention for SHM systems, the use of wired sensor technologies has seldom been used for the SHM of tall buildings. Therefore, vibration measurements resulting from strong typhoon threats were carried out within the Di Wang Tower, by Ou et al (2005), using wireless smart sensors technologies.

The Di Wang Tower implemented an advanced smart sensor network which composed of various wireless sensor nodes, utilising ADXL202 accelerometers (Lynch and Loh 2006). The deployed wireless accelerometers are capable of measuring the dynamic response of the building to vibrations caused by environmental loads; this data is then transmitted to the base station. Utilisation of such state-of-the-art smart sensor accelerometer technology, applying the MICA Mote processing platform, provides the ability to measure the structural integrity of the Di Wang Tower in real-time, at low-cost and low power consumption.

3. Results

Vibration tests conducted within the Alamosa Canyon Bridge case study with the Crossbow CXL01LF1 MEMS accelerometer drew out several important results which demonstrate the benefits of wireless smart sensors for structural health monitoring. These include the minimal installation time of wireless sensor nodes to the structural steel girders by magnetic mounts over the cable-based technology; with the network being installed in approximately half the time (Lynch et al 2003). Furthermore, the Crossbow CXL01LF1 MEMS wireless accelerometer prototype was capable of collecting sensor data at almost exactly the same accuracy as that of the cable-based system. Demonstrating accurate data recording from wireless technologies.

Use of the Proxim RangeLan2 network transceiver within the Crossbow CXL01LF1 sensor allows for an energy efficient wireless sensor network while providing a large communication range up to 450 feet (137m) within heavy construction material. This communication data range would allow for significant distance between distributions of sensor nodes within a building, therefore reducing the quantity of sensors required, and subsequently sensor network costs.

However, the WiMMS processing platform installed within the Crossbow CXL01LF1 accelerometer delivers a limited size of memory capacity thus, reducing the amount of data that can be stored and transmitted from the sensor. If continuous earthquake tremors resulted in significant amounts of data, the opinion of the CXL01LF1 MEMS accelerometer would be that it is incapable of measuring continued vibration data. Concluding that the use of the WiMMS processing platform is unsuitable for the installation within high-rise structures.

The five Crossbow CXL01LF1 accelerometers mounted evenly across the Alamosa Canyon Bridge field test established limitations presented through the necessity of a 9V lithium battery pack to supply power for the sensor node. Due to the limited fifteen hours of continuous monitoring it delivers, the application of these sensors within inaccessible structural elements in a high-rise structure would make it difficult to charge or replace these batteries throughout the life-cycle of the building. Demonstrating that further research is required to advance this system.

Unattended and remote condition monitoring within the SFOBB project has established further smart sensor technologies which could provide unattended structural monitoring through the use of AE technology. The AE sensors demonstrated a resilient and robust installation system for harsh, outdoor environments and were installed using a cyanoacrylate adhesive which allowed for ease of installation. Another major advantage of employing this sensor technology is presented by the ability of the main board to perform data collection from the various AE nodes, which would allow for numerous sensors to be deployed across a high-rise building. These nodes have the capability to detect mechanical deformation within a structural component when a material undergoes stress, this stress then creates transient elastic waves. These waves are converted into electrical signals for full signal processing, crack location detection and alarm signalling; therefore, minimising the need for continuous visual inspections by creating an alarm monitoring and notification solution to SHM.

Nevertheless, AE sensors need to be tailored to fit independent structures due to the differentiating signals produced from a variety of materials, creating higher development costs for commercial application. However, the adoption of an alarm signal systems would ensure any measured vibrations or miniscule cracks which appeared within a material would be highlighted immediately, reducing resource costs to repair or maintain the structural element.

Results from the Di Wang Tower case study and the use of the ADXL202 accelerometer confirm that the sensor technology utilised within a high-rise building is similar to that of any structural infrastructure. It is a low cost, low power sensor in which both dynamic and static acceleration can be measured across 2 axes. The Linksys WAP11 wireless operating system provides an excellent prototype of a high-speed data range up to 11000kbps; one of the largest data transfer speeds established within this research, across a range of 300 - 500 feet (91m – 152m). Additionally, the MICA Mote processing platform employed is the most commercialised platform out of the smart sensors analysed within this research due to its open source wireless platform thus, higher data memory for continuous real-time monitoring.

4. Discussion

Detailed discussion on the findings collated within this research provide an understanding of the role in which advanced smart sensor technologies play in the monitoring of structural integrity of high-rise buildings within high seismic areas. There are copious amounts of research within academic literature which emphasise the importance of developing smart city initiatives in order to create sustainable future proof urban infrastructure. It can be expected that findings presented through a quantitative case study analysis will corroborate the opinion that smart wireless technology has the potential to play a vital role within the monitoring of structural integrity in high-seismic areas.

The Alamosa Canyon Bridge case study demonstrated the operative monitoring and processing capability of a wireless sensor in comparison to a wired system, with one of the main constraints of sensor implemented highlighted through interview analysis being that the associated costs of implementing wired SHM systems within high-rise buildings would be infeasible. Concluding that wireless sensor technology is a more feasible and adventitious option as demonstrated by the highly reliable and precise data they generate: at a drastically reduced cost.

One important objective to consider in the practical implementation of sensor technologies within high-rise buildings would be the quantity of sensor nodes required. Alamosa Canyon Bridge case study analysis demonstrated that the lack of traditional coaxial wires can allow the sensors to be positioned anywhere across a regular structural element. Providing an effectual understanding of various smart sensor technology communication networks.

Analysis of the SFOBB project outlined various practical constraints with implementation of smart AE sensors. Research illustrated that there are a limited number of AE sensor nodes which can be connected to a single main board interface. If this system was to be installed within a high-rise structure, there would be the requirement of various main board systems, demanding additional space for installation. Furthermore, the adoption of a cyanoacrylate adhesive eliminates any air between the substrate and the sensor, providing an effective coupling method. Yet if deployed outdoors, this coupling may become weathered, therefore fails to ensure an effective connection technique.

Review of the wireless sensor nodes deployed to enable continuous sensing, communication and damage detection within the Di Wang Tower established a deeper understanding of smart sensors for improved structural integrity monitoring. In the context of high-rise buildings, many structural responses to loading and strain will be regularly monitored in real-time within high seismic areas. The commercialised platform with ‘off-the-shelf components’ which was utilised would ensure the cost of the sensor nodes would be as low as possible. If ‘off-the-shelf’ parts are utilized, field deployment costs can be kept to a minimum and therefore have the potential to drastically reduce the main operational cost constraints.

One key objective to achieve in the development of the research aim is the comprehension of smart sensor data management techniques and communication network operations. With the significant increase of smart sensor technologies and devices connected to the IoT for big data analytics, management of sensor data is becoming an increasingly important consideration. Plageras et al (2017) state the IoT is the key for the control and the surveillance of ‘Intelligent Buildings’. Technological advancements have allowed for advanced smart sensors to filter data which focus on high impact and vibration measurements, allowing for simpler interpretation of data and monitoring of asset health across a wireless network. The real time monitoring and data management achieved through automatic scheduled readings of sensor data can present a highly efficient strategy for data management techniques within a high-rise building to improve safety and reliability of infrastructure by detecting damage before it reached a critical state.

A significant finding discovered within this research was the benefits in which the implementation of an alarm signal system would provide within a high-rise SHM communication network. Information gathered from the smart AE sensors implemented on the SFOBB project demonstrated the effectiveness of an alarm signal in securing the asset health of structural elements if a threshold vibration limit was measured. Application of an alarm signal system would ensure evacuation procedures would transpire when a high level of vibration or structural damage was recorded within the high-rise structure, ensuring safe evacuation of occupants before a fatal collapse.

A key characteristic in the understanding of smart sensor data management would be to increase the perception of data and network security. A vital characteristic highlighted within industry research, in which interviewees further corroborated, was that security was an important aspect to consider. Suggesting that LoWPAN and ZigBee would be the most appropriate and secure communication networks while also allowing for further password protection if required. One interviewee discussed the advantages offered through cloud storage, concluding that for secure and reliable data management systems, verification procedures which allow only certain authorised devices to join the wireless network and storage systems would be highly manageable.

Communication network operations are critical to recognise in the development of smart sensor technologies for SHM within high-rise buildings. All three smart sensor technologies within the analysed case studies employed some spectrum of RF wireless technology, such as Bluetooth or ZigBee networks. Al-Sarawi et al (2017) states that two of the most commonly used wireless communication network systems are that of LoWPAN and ZigBee, implying that long range RF wireless communication technology is the most pertinent for advanced smart sensor applications in high-seismic areas.

The objective in outlining constraints in the practical application of advanced smart sensor technologies was achieved though analysis of the key connections recognised within field validation tests. This was the constraints of battery power and high installation costs. Kintner-Meyer (2005) state that in building automation applications, power consumption is of critical importance. Obtaining a single power source for embedded sensors that do not require batteries is still a major limitation to the application of advanced smart sensor technology.

Each case study anaslysed relied on some form of battery power for operation. Kintner-Meyer (2005) claim that for building maintenance, a smart sensor must have a minimum of three to five-year battery life in order to be efficient. Analysis of the case study research concluded that the battery power utilised within each project would fail to meet this standard. There are strategies in which power consumption can be reduced, for example lowering frequency ranges which are monitored as well as the regularity in which the sensor performs an assessment of structural integrity. This process may allow the battery life of the sensor to be extended, however it is still highly unlikely that batteries alone can provide power for the entire lifecycle of the building. Discussions from industry professionals further supported this outcome, with interviewees explaining the constraints presented with battery power alone for advanced smart sensors due to the requirement of continuous rotation of batteries or wired power sources.

One interviewee discussed the advantages in the implementation of a solar power aspect within smart sensors. Although a successful protype was produced, it can be argued that sunlight is not always available for application within inaccessible areas; concluding solar power would be infeasible within structural elements. Therefore, conclusions were drawn that battery power remains a vital constraint and an infeasible option for wireless sensors in the construction of high-rise buildings.

The implications of the evolution of smart sensor technology and intelligent buildings requires the practice of Architectural Technology to rethink their traditional involvement in building management. With the most significant transition within the industry due to buildings becoming data-rich environments from omnipresent sensors of activity. With this rise in IoT, big data analytics and cloud capabilities, no single organisation can harvest the full potential of a fully smart environment; therefore, the architecture profession would require innovative industry collaborations for efficient management systems, such as Siemens' partnership with Capgemini. Furthermore, with an ambiguous understanding of regulations and smart sensor protocols; the future intelligent building concept is in it's infancy.

The limited understanding of the role in which smart sensor technologies currently play within industry practice of SHM in high-rise buildings ensures the outcomes of this research are significant due to the increased awareness that cataclysmic events, such as earthquakes, pose a critical threat to the structural integrity of urban infrastructure in cities of the future. The comprehensive understanding gained within academic and professional industry research provided practical insight into both benefits and limitations across a variety of advanced smart sensors and their role in monitoring deteriorating infrastructure. The key constraints of costs and battery power are the main limitations in smart sensor technologies for SHM applications in high-rise buildings. The research recognised that although there may be significant initial upfront capital required for practical installation of wireless sensor technologies, the perceived benefits for lifecycle maintenance outweigh the cost restrictions. Utilisation of sensing technologies provide insight into a buildings response to vibrations, stresses and strains with real-time, continuous monitoring. This therefore improves operational efficiencies, extending the life of assets, reducing the risk of catastrophic failures as well as improving sustainability for Smart Cities of the future.

5. Conclusions

The vision of future urban developments is continuously evolving in order to efficiently manage the rapid increase in urbanisation expected within the coming years. Structural health monitoring is one of the most important components in the maintenance technology for civil infrastructures. With the additional rising occurrence of earthquake tremors threating the structural integrity of critical urban infrastructure within the U.S; innovative technological advancements may present the ability to ensure long-term planning for safe and reliable urban infrastructure. Reoccurring earthquakes with low magnitudes will still cause major structural damage over the life span of a high-rise building, and with an estimated three-quarters of all deaths in earthquakes due to building collapse (Cross 2015), regularly occurring earthquake tremors present an immense threat.

These pressures create an urgency for cities across the globe to find smarter approaches to solving issues regarding the safety of its critical urban developments. The analysis conducted of previous academic literature provided a comprehensive understanding of the characteristics of future smart city initiatives that aim to alleviate the threats that climate change and rapid urbanisation present. Academic literature states that education is one vital part of the future of Smart Cities along with the development of intelligent digital technology to promote performance within buildings; hence the ability to monitor and control critical infrastructure to respond to global challenges.

The role which advanced smart sensor SHM technologies play within high-seismic areas was established through both case study and industry research, developing the understanding that the goal of SHM is to improve safety and reliability of infrastructure by detecting damage before it reaches a critical state. Therefore, an awareness was obtained that a smart structure utilises sensing technologies to provide insight into its response to vibrations, stresses and strains with real-time, continuous monitoring. To ensure modern city infrastructure is robust, resilient and adaptable to the consistently changing environment, this research presents a variety of advanced smart sensor technologies which can offer an effective SHM system over the expected lifespan of infrastructure. This is made possible due to the physical and digital worlds converging; bringing greater efficiency and new opportunities.

References

Cross, R. (2015). *Nepal earthquake: a disaster that shows quakes don't kill people, buildings do*. Retrieved from https://www.theguardian.com/cities/2015/apr/30/nepal-earthquake-disaster-building-collapse-resilience-kathmandu

Farrar, C.R., Cornwell, P.J., Doebling, S.W. & Prime, M.B. (2000). *Structural Health Monitoring Studies of the Alamosa Canyon and I-40 Bridges*. New Mexico: University of California.

Grover, A & Walia, N. (n.d.). *Sensors and Smart Cities.* Carleton University.

Hancke, G., Silva, B & J.R.Hancke (2013). The Role of Advanced Sensing in Smart Cities. *Sensors*, 13, 393 – 425.

Johnson, M. Ozevin, D., Washer, G., Ono, K., Gostautas, R. & Tamutus, T. (2012). Acoustic Emission Method for Real-Time Detection of Steel Fatigue Crack in Eyebar. *Journal of the Transportation Research Board*, 2313(-1), 72-79.

Kintner-Meyer., M.C.W. (2005). Opportunities of wireless sensors and controls for building operation. *Energy Engineering*, 102(5), 139-152.

Klikowicz, P, Salamak, M and Poprawa, G. (2016). Structural Health Monitoring of Urban Structures. *World Multidisciplinary Civil Engineering Architecture Urban Planning Symposium 2016*, 161, 958-962.

Lynch, J and Loh, K. (2006). A Summary Review of Wireless Sensors and Sensor Networks for Structural Health Monitoring. *The Shock and Vibration Digest*, 38 (2), 91-128.

Lynch, J., Sundararajan, A., Kincho, H.L., Kiremidjian, A., Carryer, E., Sohn, H. & Farrar, C. (2003). Field validation of a wireless structural monitoring system on the Alamosa Canyon Bridge. *Annual International Symposium on Smart Structures and Materials*.

Ou, J., Li, H., Xiao, Y. & Li, Q (2005). Health dynamic measurement of tall building using wireless sensor network. *Proceedings of the Smart Structures and Materials 200*5, 205–216.

Plageras, A.P., Psannis, K.E., Stergiou, C., Wang, H. & Gupta, B.B. (2017). Efficient IoT-based sensor BIG Data collection – processing and analysis in smart buildings. *Future Generation Computer Systems*, 82, 349-357.

RICS. (2017). *Smart Cities*. Retrieved from http://www.rics.org/uk/knowledge/glossary/smart-cities/

Slowey, K. (2019). *Los Angeles Development Booming*. Retrieved from https://www.constructiondive.com/news/los-angeles-development-booming/550181/

USGS (2019). *Earthquake statistics*. Retrieved from https://earthquake.usgs.gov/earthquakes/browse/stats.php

Crane camera image preparation for automated monitoring of formwork and rebar progress

Antti Aikala*, Mustafa Khalid, Olli Seppänen and Vishal Singh
Department of Civil Engineering, Aalto University, Finland
* email: antti.aikala@aalto.fi

Abstract

Crane cameras are emerging as a cost-effective technology for enhancing situational awareness at construction sites. Crane camera images in combination with point clouds can facilitate automated progress monitoring of sites, which can lead to significant time and cost savings in comparison to manual inspection methods. In this work, we focus on preparing crane camera images for monitoring the progress of formwork and rebar used for laying concrete slabs. Preparation is needed, because the view angle and position of the target slab are changing between images because of crane boom rotation. Furthermore, vertical distance from the camera to the topmost slab changes as the building rises. Our target is to rotate, crop and rescale the original images in such a deterministic way that the slab under construction is always shown in the result images at the same position, orientation and scale. In order to achieve that, we need to know the view angle and the positions of both the camera and the slab. Camera positions can be read from image metadata and, because the crane rotation axis position is known, the boom angle can also be calculated. We noted that the GPS information extracted from the image metadata typically has deviations that could adversely affect the transformation, and that occasionally GPS values are too erroneous to be used at all. We present experimental results from data collected at a large construction site in Helsinki, Finland.

Keywords: Progress monitoring, crane cameras, image transformation, Intersection over Union (IoU)

1. Introduction

Effective control of construction site activities requires frequent monitoring of the site. Many methods have been proposed to monitor construction sites, including handheld cameras Golparvar-Fard et al., 2015, Unmanned Aerial Vehicles (UAVs) and laser scanners. Recently, a new technique to acquire as-built data has emerged, which is the use of crane cameras. The major advantage of crane cameras over other methods is that the data acquisition can be fully automated with minimum cost and effort. Furthermore, crane cameras are non-intrusive to site operations. The photogrammetry software provider Pix4D has developed a crane camera solution for automatically taking and storing 2D overview images, uploading images into a cloud service and generating daily georeferenced 3D point clouds. Although the 3D point clouds can provide the current floor under construction, it is the 2D images that provide the richest information about the state of the slab. Additionally, although there is only one 3D point cloud generated per day, there are multiple 2D images. Thus, construction progress can be monitored with higher temporal granularity using 2D images, and we will focus in this paper on the analysis of 2D images.

One useful type of information that can be inferred from crane camera images is the progress of formwork and rebar. However, in order to effectively perform progress analysis, crane camera images need substantial preprocessing. Two key issues need to be addressed by the preprocessing step: first, the changing *scale* of images as the building is built and increases in proximity to the crane camera and second, the changing *orientation* of the images as the crane rotates about its axis. Both issues can adversely affect the detection of slab edges, which can in turn degrade the formwork and rebar analysis. Additionally, keeping track of the correct scale can allow us to leverage size features (such as thickness) to distinguish rebar from formwork, while knowing that the correct orientation can allow us to leverage the vertical orientation of rebar.

In this paper, we present our method of executing the preprocessing step, including the assumptions we make about the data. We also explore the most important factors for successful preprocessing, evaluate the quality of our preprocessing and discuss possible ways of improving the task. This paper is organized as follows: Section 2 discusses related work over image-based formwork and rebar progress monitoring. Section 3 describes image and other data available for the preprocessing and our preprocessing method. Section 4 presents the results and discussion, quality of input data and evaluations of area detection. Section 5 lays out the conclusions and future work.

2. Related Work

Tuttas et al. (2016) presented a comparative analysis of data acquisition using crane cameras, UAVs and hand-held cameras. They pointed out that crane cameras are the best solution when daily images of building slabs are required, since the data acquisition can be fully automated and the cameras provide a nadir view of buildings. Turkan et al. (2014) presented a method to label column, floor and wall objects in the as-designed model as being in either “built”, “formwork” or “rebar” state. Taking a Terrestial Laser Scanned (TLS) point cloud registered with the BIM model, they noted that the percentage of object recognition varied differently with respect to a Euclidean distance threshold for different states of construction. This method does not capture the percentage completion of formwork and rebar, which is better done using 2D images.

Braun, et al. (2015) proposed a method to combine temporal information of the construction state with geometric matching of the as-built point cloud and as-planned model using precedence relationship graphs. However, this method is also not capable of inferring the formwork and rebar progress of floor slabs. Goldapar-Fard et al. (2015) showed how unordered images and time-labelled 3D plans can be used in progress analysis. One important part in their method is the detection of occlusions. However, the 3D voxel side length is 6 cm that is probably too coarse for detection of rebars which have a typical thickness of only 1 cm. Analysing the percentage completion of formwork and rebar on floor slabs requires a level of detail not present in 3D point clouds, to which previous works have typically limited their progress analysis. However, the details like rebars are clearly visible in 2D images.

The global positions of the crane cameras vary according to the horizontal angle of the crane jib and the installation position of the camera in the jib (Pix4D, 2017). Furthermore, the height difference between the camera in the jib and the target slab affects to the scale of the slab images (Tuttas, et. al, 2016). For the work progress analysis of the slab work, it is desirable to get the nadir view images with fixed orientation and scale that allows direct comparison of the slab area in the original images with the corresponding 2D floor plan. Assuming that the position of the camera and slab are known, this image preparation can be carried out with the geometric transformation using, for example, open source OpenCV package (Bradski, et al., 2008). To the best of our knowledge, this is the first work that deals with the preparation of crane camera images for formwork and rebar progress analysis.

3. Methodology

3.1 Data description

Images used for this analysis were provided by a crane camera solution by Pix4D implemented at a large construction site in Finland. Two cameras were installed on the boom of a tower crane located centrally on the site. The cameras were located approximately 13 and 37 meters from the rotation axis of the crane, respectively and their viewing direction was towards the ground. The vertical height of the crane boom, and thus of the cameras, was about 100 meters from sea level. Images used for this work were taken between 5th July and 2nd November 2018, in total 5361 images from 39 working days. In addition to the 2D images, georeferenced daily 3D point clouds were available on the cloud. The height of the building could be inferred from these point clouds.

The areas of interest were two horizontal floor slabs from a residential building. We labelled the slabs A and B as shown in Figure 1. The two slabs were built at a different pace, so the floor number being built was different for each slab. Selection of the areas of interest was based on visibility of the areas in the pictures, because these areas were closest to the crane and were thus viewed relatively often by the crane cameras. The images contained some useful metainformation for the analysis, such as time, GPS position and camera number. On the other hand, we knew from the BIM model and site plans the positions of the slabs and the crane. Figure 1 illustrates the north direction, positions of the crane, camera movement lines and areas of interest (slabs A and B) on a map that has been rotated in the orientation of the local site coordinate system.

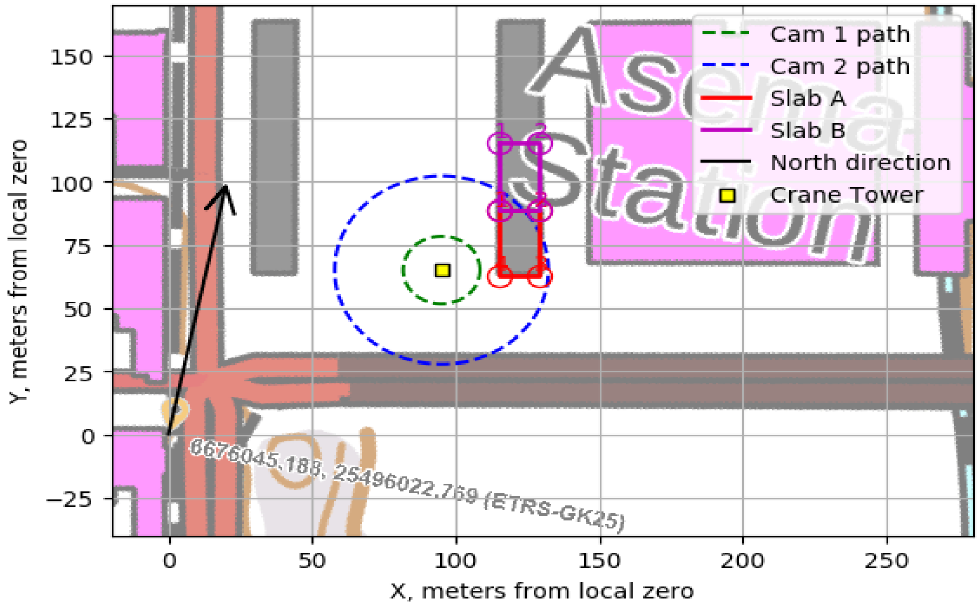


Figure 1. Background map in the local site coordinate system and the key elements for the analysis

Since the cameras were in nadir orientation, the viewing directions of the camera did not change when the crane moved. This simplified the processing, because the sensor could be assumed to be parallel to the horizontal slab plane. Only the positions and yaw angles of the cameras changed according to the rotation of the crane boom. Additionally, it was assumed that the GPS values in the image metainformation were reasonably accurate. Furthermore, we assumed the images were undistorted, since no distortion was visually discernible. For the distorted case, calibration would be needed. The focal length per detector width was approximately 28 mm for 35 mm film.

3.2 Preprocessing algorithm

The preprocessing algorithm selects the desired slab area from the crane camera images. It uses camera and area positions to determine where in the original image pixel area is the area of interest.

A simplified flowchart of the preprocessing algorithm is presented in Figure 2. The inputs are shown on the left side of the flowchart. Inputs are grouped into **Static** and **Varying** data. Static data contains inputs which can be set when the system is set up at the beginning of the construction process. Varying data depends on the target area and the image to be converted, its time value, the actual camera position and the pixel values of the image. Subfunctions are shown as yellow circles. Each subfunction provides one main result, shown in the text box next to the function. The final result of this algorithm is a transformed image. In the flowchart, the lines show data flows. All inputs of one function have the same colour.

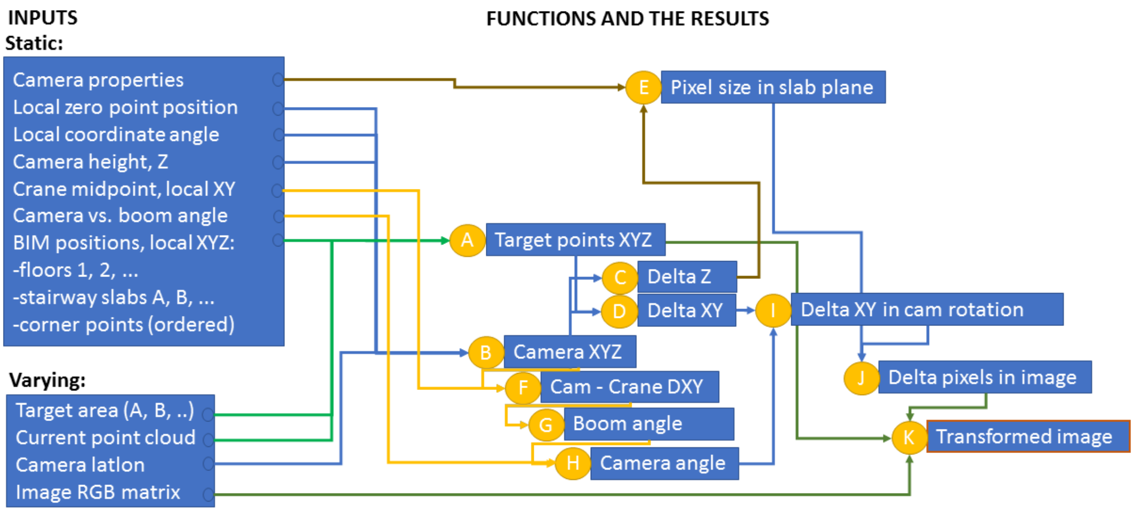


Figure 2. Flowchart diagram for automatic 2D image rotation and cropping.

The inputs to the algorithm are explained in the following. *Camera properties* define the camera's focal length for 35mm film and the number of pixels. *Local zero point position* and *local coordinate angle* are used for coordinate changes from Latitude and Longitude values to local coordinate XY values. For example, in our test case, the site coordinate zero point position and the angle between coordinate systems can be seen from Figure 1. The angle was 11.5 degrees and the local zero point was in Graus-Krueger (ETRS-GK25) coordinates, which we converted to latitude-longitude values (60.1971945, 24.9282963). *Camera vs. boom angle* is the angle between the direction of the boom and the rotation of camera. Since the camera installation was fixed, this value is constant and was estimated from the images to be 180°. Positions of the areas of interest were extracted from the design model (BIM model) and stored as a table; each floor slab has multiple corner points in the form of X and Y values. Heights, i.e. *Z* values, were also read from the BIM model and specified for each floor separately.

Varying inputs are defined by the area of interest under consideration and the particular image being converted. In addition to the actual image data matrix of colour pixel values, each image has some metainformation such as time, GPS position, camera index value, etc. With the time value, we could refer to the correct point cloud in order to obtain the current height of the slab being analysed.

We now define the functions depicted in the flowchart:

Function A uses the BIM model to determine the area of interest corner point locations in local coordinates. **Function B** converts image latitude and longitude GPS values to local (X, Y) coordinates. It first converts all latitude and longitude coordinates to UTM easting and northing coordinates (E and N), then it subtracts the local zero point position from the image coordinates and rotates the difference values in order to obtain the image position in local coordinates (XY_{Image}):

$$XY_{Image} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \times \left(EN_{Image} - EN_{zero\ position}\right) \quad (1)$$

where α is the angle between local Y direction and global North, EN_{Image} is the image's global *(E, N)* position and $EN_{zero\ position}$ is the global position of the local zero point *(X = 0, Y = 0)*.

Functions C and **D** calculate the vertical difference and horizontal differences between the slab's corner points and the camera. **Function E** estimates the size of one pixel in the slab (formula 2), which is needed for scaling real world metric differences to differences expressed as pixels. It uses vertical difference from camera to slab and camera properties, such as focal length, sensor width and corresponding number of pixels. Note that we have square pixels, but lengths were calculated for both dimensions, image height and width, separately, allowing the method also to be used with special sensor types.

$$L_{px} = \frac{Z * L_{sensor}}{\boldsymbol{f} * N_{px}} \quad (2)$$

where L_{px} is the slab surface length of one pixel, Z is the vertical difference between camera and slab, L_{sensor} is the length of the sensor in the direction of L_{px}, f is the focal length and N_{px} is the number of pixels in the sensor in the direction of L_{px}.

Final conversion from metric value differences to pixel index difference can be made when the rotation of the image is known. **Function F** calculates the horizontal difference from the crane boom's rotation point to the camera and **Function G** calculates the boom rotation angle in the XY plane, which has a value of 0 when the boom is in direction X from the crane. **Function H** gives the camera image rotation in the XY plane. **Function I** uses camera rotation information and changes horizontal differences from the local XY coordinate directions to directions of the camera sensor. Then **Function J** scales metric differences to pixel differences.

Function K combines corner point differences in pixels to the East and North directions and the rotation of the camera, and returns corner point pixel differences as image index values. Note that the camera centre point is always in the middle of the image, for the nadir orientation. Finally, **Function L** uses corner point indices to generate the final image. The scaling of the transformed image can be fixed when the original slab size is known. This size is calculated from the slab corner XY coordinate positions. The result of function L is a *rotated*, *cropped* and *rescaled* image.

4. Results and Discussion

In this section, we will present an evaluation of the accuracy of the *camera positions* as the crane rotates, which are simply the GPS values obtained from the camera every time an image is taken. Then, we will *evaluate the match* between the slab area detected by our algorithm and the ground truth, which is taken manually by selecting the slab area.

4.1 Accuracy of camera GPS values

Ideally, as the crane rotates about its axis, the camera positions should trace a circle whose centre point is in the crane midpoint and whose radius is the location of the camera on the crane boom as measured from the crane mid-point. The crane position was given, but the camera location on the boom was estimated as the median of Euclidean distances between the camera GPS values for multiple images and the crane midpoint. Some images did not contain GPS values (we could not determine the reason for this). Two images contained clearly false GPS values. However, reasonably accurate positional data was available for 2086 images taken with camera 1 and 2009 images taken with camera 2 with positions near the crane, which made it possible to estimate the GPS accuracy. Figure 3 shows camera 1 and 2 image positions in local coordinates. In addition, it shows the estimated paths of the real camera locations. Estimated circle path radius values were 13.4 m for camera 1 and 37.2 m for camera 2.

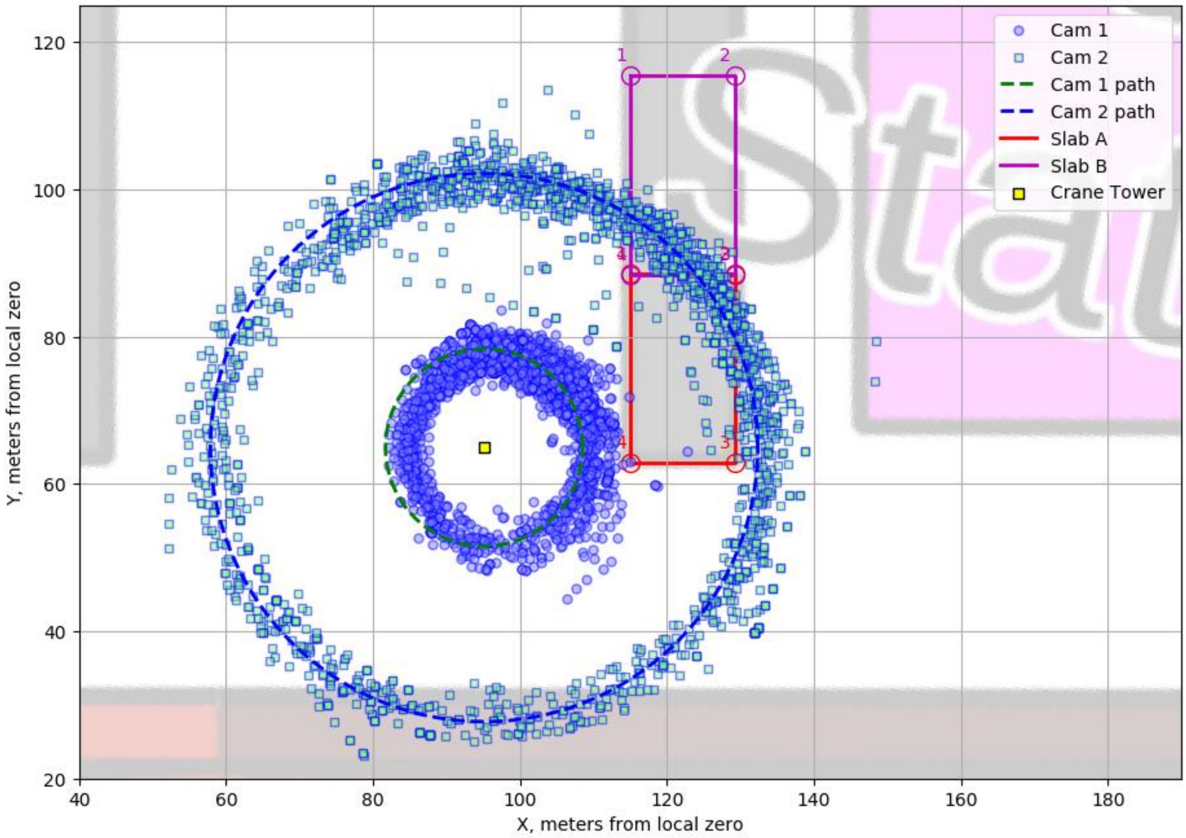
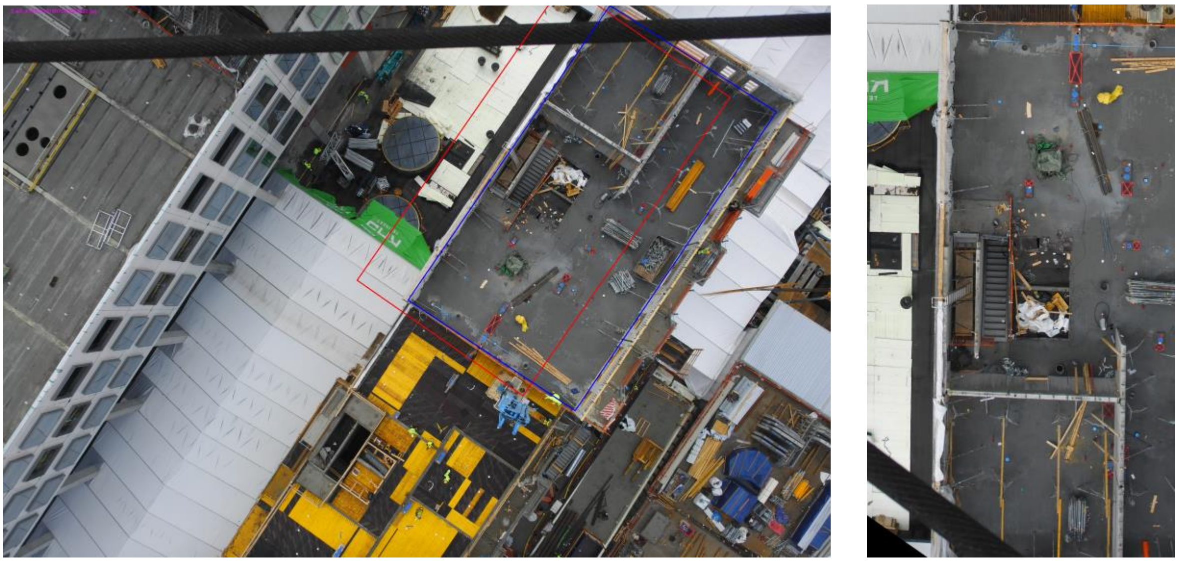


Figure 3. Crane camera image locations and cameras' path on the background map

Camera 1 image position data indicates that the actual crane midpoint might be about 2 meters away (in the X direction) from the crane coordinates available to us (which we assume to be the crane midpoint). However, the possibility of this error is not discernible in the results for camera 2. With the available crane midpoint, the standard deviations for image distance from the centre point are 2.4 and 2.9 meters for cameras 1 and 2, respectively. If we instead take the crane midpoint to be 1.8 meters further in the X direction, the deviations would be 1.9 and 2.9 meters for cameras 1 and 2, respectively. However, regardless of the crane midpoint, the camera position (GPS) values deviate significantly from the reference circle, especially considering that the width of the area of interest is only 10 meters. Furthermore, despite lying on the reference circle, the camera position values might still be offset from the actual position of the camera. This type of error can lead to the calculation of an incorrect rotation angle for the orientation-correction part of our algorithm.

4.2 Evaluation of the slab area selection



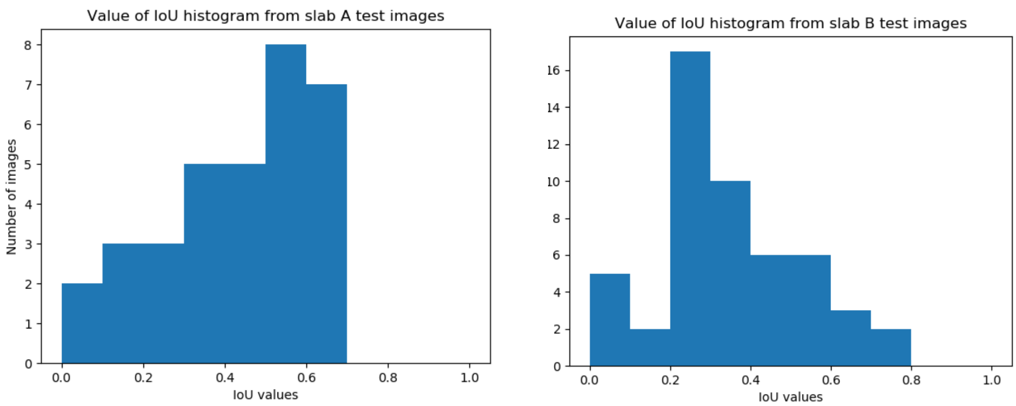
(a) (b)

Figure 4. (a) A sample image from our dataset (taken on 6th July 2018 with Camera 2). The red box shows the estimated boundaries of the slab and the blue box shows the ground truth (selected manually). (b) The detected area is selected, rotated and scaled according to local coordinates

Figure 4 shows the result of a complete implementation of the algorithm. Figure 4 (a) shows the estimated slab boundaries. To evaluate the match between the estimated and ground truth boundaries, we used the metric *Intersection over Union (IoU)* (Weidner, 2008), in which the intersection of the estimated and reference areas is divided by their union. Thus, an IoU value of 1 means perfect overlap and a value zero means no overlap. For the Figure 4 result, this value is 0.57. For the estimated area *S* and the reference area *R*:

$$IoU = \frac{S \cap R}{S \cup R} \tag{3}$$

To evaluate IoU, we manually specified 33 images from slab A and 51 from slab B. Our main selection criteria for the images was that the slab should be completely visible in the image. Histograms of IoU values plotted against number of images are shown in Figure 5.



(a) (b)

Figure 5. Results of the algorithm for slabs A and B

The histograms show that average IoU values lie around 0.4. Considering that the IoU value of

Figure 4a detection was 0.57, we can conclude that the results are not adequate as such. Thus, some additional methods are needed to improve the results.

5. Conclusions and future work

In this paper, we presented a method for removing the rotation effect of crane camera images and thus enhancing further analysis of the images. The idea was to use camera and area positions for rotation, scaling and cropping of the input images. We compared the results of the algorithm with a reference set and found that the IoU was on average 0.4. We noted that the error in image GPS positions has a significant adverse influence on the slab detection accuracy. However, despite the error, the algorithm is able to select and rotate the approximate area of interest, which can be expanded according to a pre-specified threshold to ensure that the entire slab is selected.

If we acquire the accurate crane mid-point position and camera installation points in the boom, we could accurately infer the camera's circular path as the crane rotates. With this information, we could adjust image positions to the nearest position in the path. This would decrease errors in the rotation angle calculated by our algorithm. The algorithm could also be combined with a simple edge detection technique, which could fine tune the rotation of the image and thus improve the slab detection accuracy. Additionally, we intend to explore the use of 3D voxel traversing to identify occlusions and thus remove regions in the image that are not part of the slab.

Acknowledgements

We thank YIT for providing the data for this study. The work was supported by the Reality Capture research project funded by Business Finland, Aalto University and a consortium of 5 companies.

References

Bradski G. and Kaehler, A. (2008) Learning OpenCV

Braun, A., Tuttas, S., Borrmann, A., & Stilla, U. (2015, 6). Automated Progress Monitoring Based on Photogrammetric Point Clouds and Precedence Relationship Graphs. Proceedings of the 32nd International Symposium on Automation and Robotics in Construction and Mining (ISARC 2015). International Association for Automation and Robotics in Construction (IAARC). doi:10.22260/isarc2015/0034

Eickeler, F., & Jahr, K. (n.d.). PREDICTION AND SIMULATION OF CRANE BASED CAMERA CONFIGURATIONS FOR CONSTRUCTION SITE MONITORING.

Golparvar-Fard, M., Peña-Mora, F., & Savarese, S. (2015, 1). Automated Progress Monitoring Using Unordered Daily Construction Photographs and IFC-Based Building Information Models. Journal of Computing in Civil Engineering, 29, 04014025. doi:10.1061/(asce)cp.1943-5487.0000205

Pix4D. (2017, March 27). Crane camera site surveying. Retrieved from https://www.pix4d.com/blog/crane-camera-site-surveying

Turkan, Y., Bosché, F., Haas, C. T., & Haas, R. (2014, 4). Tracking of secondary and temporary objects in structural concrete work. Construction Innovation, 14, 145-167. doi:10.1108/ci-12-2012-0063

Tuttas, S., Braun, A., Borrmann, A., & Stilla, U. (2016). Evaluation of acquisition strategies for image-based construction site monitoring. ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 41, 733-740.

Visualization and Simulation Techniques

Multi-Objective Optimisation for Tuning Building Heating and Cooling Loads Forecasting Models

Saleh Seyedzadeh[1,3*], Farzad Pour Rahimian[2], Parag Rastogi[3], Stephen Oliver[1,3], Ivan Glesk[1] and Bimal Kumar[4]

[1]Faculty of Engineering, University of Strathclyde, Glasgow, UK

[2]School of Science Engineering and Design, Teesside University, Middleborough, UK

[3]arbnco, Glasgow, UK

[4]Faculty of Engineering & Environment, Northumbria University, Newcastle, UK

*email: s.seyyedzadeh@gmail.com

Abstract

Machine learning (ML) has been recognised as a powerful method for modelling building energy consumption. The capability of ML to provide a fast and accurate prediction of energy loads makes it an ideal tool for decision-making tasks related to sustainable design and retrofit planning. However, the accuracy of these ML models is much dependant on the selection of the right hyper-parameters for specific building dataset. This paper proposes a method for optimising ML model for forecasting both heating and cooling loads. The technique employs multi-objective optimisation with evolutionary algorithms to search the space of possible parameters. The proposed approach not only tune one model to precisely predict building energy loads but also accelerates the process of model optimisation. The study utilises a simulated building energy data generated in EnergyPlus to demonstrate the efficiency of the proposed method, and compares the outcomes with the regular ML tuning procedure (i.e. grid search). The optimised model provides a reliable tool for building designers and engineers to explore a large space of the available building materials and technologies.

Keywords: Building energy loads, Building energy prediction, Machine learning, Model optimisation

1. Introduction

There have been several approaches proposed to enhance the energy efficiency of buildings in many countries during the last couple of decades. For instance in Europe, it was estimated in 2010 that 60 billion Euros could be saved annually by improving EU buildings' energy performance by 20 per cent (X. Li, Bowers, & Schnier, 2010).

Every attempt to optimise buildings' energy performance involves series of calculations to estimate the energy consumption and create an index such as Energy Performance Indicator (EPI) or Energy Use Intensity (EUI) from the measured data (T. Hong, Koo, Kim, Lee, & Jeong, 2015; Nikolaou, Kolokotsa, Stavrakakis, Apostolou, & Munteanu, 2015). Most prevailing optimisation methods are simulation-based where the energy-related objectives (i.e. energy consumption or gas emission) are calculated by a Building Performance Simulation (BPS) tool such as EnergyPlus, TRNSYS or ESP-r. This approach limits the computation complexity of the algorithms to BPSs' calculation time. As such, when a large number of solutions are defined, the calculation and optimisation process may become extremely costly to handle. For this reason, most of the studies which focused on decision making for energy performance improvement of buildings either investigated basic or simple optimisation models or targeted retrofitting only one or two parts of envelopes to pare-down total calculation time and cost. It is also noted that the majority of studies targeted residential buildings, and there are only a few examples of research related to non-domestic buildings. A key component of achieving global development and meeting climate change mitigation targets is the optimisation of the building stock. This process requires significant testing and planning to deliver.

With the tremendous growth in the amount of valid and attainable datasets of structures and collection of Big Data from smart buildings, there is an increasing interest in the employment of Artificial Intelligent (AI) methods specifically Machine Learning (ML) (Seyedzadeh, Rahimian, Glesk, & Roper, 2018).

The use of ML models needs particular consideration of the accuracy and suitability of the data and relationships inferred from the data. It has been demonstrated that the process of tuning a model not only increases the predictive accuracy but also reduces model complexity, ease of use, and consistency of predictions (Seyedzadeh, Rahimian, Rastogi, & Glesk, 2019).

ML techniques have been widely used for modelling building energy loads and performance. Traditionally, the defaults values for hyper-parameters have been used in this field, however, in recent years researchers have started to tune the ML models to have more accurate predictions of energy metrics (Ahmad, Mourshed, & Rezgui, 2017; Jain, Smith, Culligan, & Taylor, 2014; C. Li, Ding, Zhao, Yi, & Zhang, 2017; Massana, Pous, Burgas, Melendez, & Colomer, 2015). Tuning ML model hyper-parameters using grid search could be very time-consuming when a complex one is chosen such as Artificial Neural Networks or models based on decision trees.

When MLs are utilised to forecasting multiple measures such as heating and cooling loads, it is required to optimise models for both the targets (Papadopoulos, Azar, Woon, & Kontokosta, 2018; Seyedzadeh et al., 2019). This procedure, in turn, increases the time required and exacerbates the usability of MLs.

To address the issues mentioned above, this paper proposes a method based on an evolutionary algorithm for optimisation of ML models for accurate prediction of both heating and cooling loads. The proposed approach uses a multi-objective optimisation (MOO) to find the most appropriate hyper-parameters for Random-Forest (RF) model. The selection of RF method is due to the high precision of in prediction and the ability to simultaneously forecast multiple targets.

The next section presents a review of previous studies and issues with tuning ML models in predicting building energy consumption. That is followed by a description of the RF method, the case study, and results from our tuning approach. The final section contains recommendations and discusses future work.

2. Background and Motivation

Machine Learning refers to a set of algorithms that can learn from existing data (features and targets) to predict outputs on new, unseen inputs. The learning algorithms are divided into two categories: supervised learning, in which the target is known, and unsupervised learning, where there is no “output” to learn and predict. Supervised learning is either one of regression or classification, in which input features (X) are mapped to one or more targets variables (Y). Unsupervised learning includes techniques such as clustering, which organises data into groups based on similarities among the samples in a dataset. Unsupervised learning is applied to an unlabeled dataset, i.e., where the there are no labels to test against, while a supervised learning algorithm detects the relation between inputs and output and used this function to predict new records.

The use of machine learning models in the analysis of buildings was first used by Kalogirou et al. (1997) to estimate building heating loads considering envelope characteristic along with the desired temperature. The work (S. A. Kalogirou, 2000) was completed in 2000 by using ANNs to predict the hourly energy demand of holiday dwellings, calculated using ZID software. Kalogirou et al. (S. Kalogirou, Florides, Neocleous, & Schizas, 2001) also used ANN to estimate the daily heat loads of model house buildings with different combinations of the wall and roof types (i.e. single vs cavity walls and roofs with different insulation applied) using a typical meteorological data for Cyprus. In that study, TRNSYS software acted as an energy evaluation engine for all cases and the data validated by the comparison of one building energy consumption with the actual measurement. Since then, ANN has been widely used for estimating building heating and cooling loads (C. Deb, Eang, Yang, & Santamouris, 2016; S. M. Hong, Paterson, Mumovic, & Steadman, 2014; Paudel, Elmtiri, Kling, Corre, & Lacarrière, 2014; Yokoyama, Wakui, & Satake, 2009), Electricity demand (Mena, Rodríguez, Castilla, & Arahal, 2014; Platon, Dehkordi, & Martel, 2015), energy demand (Dombayci, 2010; Kialashaki & Reisel, 2013; Neto & Fiorelli, 2008) and overall energy performance (Khayatian, Sarto,

& Dall'O', 2016; Wong, Wan, & Lam, 2010; Yalcintas, 2006).

Support Vector Machine (SVM) for building energy forecasting was introduced by Dong et al. (2005) and adopted by several studies for prediction of cooling and heading loads (Hou & Lian, 2009; Q. Li, Meng, Cai, Yoshino, & Mochida, 2009; Xuemei, Jin-hu, Lixing, Gang, & Jibin, 2009) electricity consumption (Massana et al., 2015; Xing-ping & Rui, 2007), and energy consumption (Chen & Tan, 2017; Jain et al., 2014; H. Zhao & Magoulès, 2010).

Ensemble ML models such as RF and gradient boosted regression trees have been introduced for decades, but their use in building energy domain is recent (Deng, Fannon, & Eckelman, 2018; Papadopoulos, Azar, Woon, & Kontokosta, 2017; Tsanas & Xifara, 2012; Wang, Wang, Zeng, Srinivasan, & Ahrentzen, 2018).

Simple models with few parameters like SVM are easy to optimise, but when the number of hyper-parameters is increased the search space becomes huge. For example, to tune an RF with six parameters, a grid search will explore more than four thousands possible configurations. That is why traditionally, the researchers mostly relied on default values for those hyper-parameters. However, such models provide far more accurate results by precise tuning in comparison with SVM or Gaussian process regression (Seyedzadeh et al., 2019). Forecasting two or more building energy measures such as heating and cooling loads at one time requires even more expertise and investigation. The use of complex model and grid search for such applications is not a viable solution, due to the complexity in time as well as selection of the ideal model.

This study proposes a framework for optimising models with several hyper-parameters and ability to predict multiple targets from the same set of features concurrently.

3. Methodology

Figure 1 demonstrates the proposed optimisation procedure for selecting the best hyper-parameters. ML models operate as a black box, so further information about the building is not required. As is clear, the first step is to select a set of features for representing the building energy system. Although data-driven methods build models with fewer variables than engineering techniques, it is crucial to generate a logical input set for ML models. These features are not necessarily raw building characteristics or weather data; instead, they could be complex variables calculated from basic ones, e.g. mean daily global radiation (H.-X. Zhao & Magoulès, 2012). The next step is to optimise the model itself.

In this study, the use of an evolutionary optimisation algorithm for selecting the best parameter of an RF model in forecasting heating and cooling loads of buildings is proposed. The proposed optimisation algorithm and machine learning model are implemented using Python programming language, and tests have been carried out on a PC with Intel Core i7-6700 3.4GHz CPU, 32GB RAM. An RF model for prediction of heating and cooling loads is also tuned using a grid search method. All models are trained and tested using 10-fold cross-validation and five thousand randomly selected building records.

In this section, first, the RF model is introduced, followed by an explanation of MOO. Then the evaluation criteria, along with the optimisation parameters, are elaborated. Finally, the description of the building dataset, which is used as the case study for the evaluation of the proposed approach will be presented.

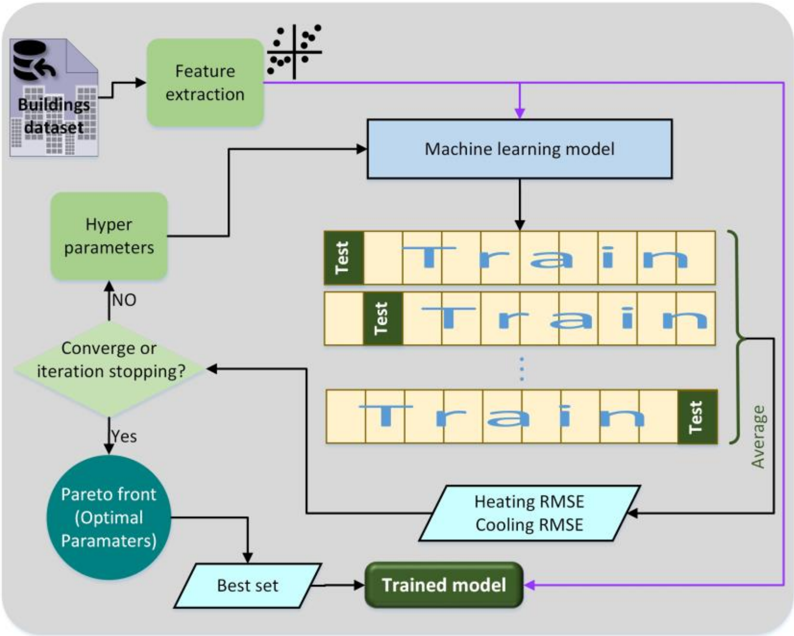


Figure 1: Schematic diagram of the proposed MOO-ML method.

3.4. Random Forest

Random forest is a collection (ensemble) of randomised decision trees (DTs). A DT is a non-parametric ML algorithm that establishes a model in the form of a tree structure. DT repeatedly divides the given records into smaller and smaller subsets until only one record remains in the subgroup. The inner and final sets are known as nodes and leaf nodes. As the precision of DT is substantially subject to the distribution of records on in the learning dataset, it is considered as an unstable method (i.e. tiny alteration in the observations will change the entire structure). To overcome this issue, a set of DTs is used and the average predicted values of all independent trees is selected as the final target. In general, RF applies bagging and boosting to combine separate models with similar information to generate a linear combination from many independent trees.

RF requires several hyperparameters to be set. The main parameter is the number of independent trees in the forest. There is a trade-off between the accuracy of model and training and predicting computational cost. Thereby, this parameter should be tuned to choose the optimal value. Other parameters include the number of features to consider when seeking for the best split, whether bootstrap (generating multiple different models from a singular training dataset) samples are used when creating trees and a minimum number of a data sample to split on nodes.

3.4. Multi-objective optimisation approach

There are several tuning methods for optimising the MLs for accurate predictions. These approaches include grid and random search techniques, evolutionary algorithms or Bayesian optimisation. Generally, these methods are applied to optimise a single objective criterion. However, in applications where two or more objective functions (i.e. heating and cooling loads) are optimised, those approaches are not adequate to designate the behaviour of the ML, and the Pareto front of multiple criteria has to be considered. Usually, for each objective, an ML is independently tuned to get the best hyper-parameters, and the most accurate model and its configuration are selected eventually. The main disadvantage of this strategy is the high time-complexity of tuning the separate models. We propose a MOO method for automated hyper

parameter selection in modelling the heating and cooling loads of a building. The proposed method reduces the time required for tuning, speeds up the model predictions and decreases human effort for implementing ML.

The general MOO problem is presented mathematically as:

Minimise:

$$F(\vec{x}) = [f_1(\vec{x}), f_2(\vec{x}), \dots, f_m(\vec{x})]^T$$

Subject to

$$g(\vec{x}) \leq 0$$
$$h(\vec{x}) = 0$$

where

$$x_i^{min} \leq x_i \leq x_i^{max} \ (i = 1,2, \dots, n)$$
$$x = [x_1, x_2, \dots, x_n]^T \in \Theta$$
$$y = [y_1, y_2, \dots, y_m]^T \in \psi$$

Here *m* is the number of objective functions which is three in our problem. Φ is the search space with *n* dimensions and identified by upper and low bounds of decision variables $x_i (i = 1,2, .., n)$.

$$x^{max} = [x_1^{max}, x_2^{max}, \dots, x_n^{max}]^T$$
$$x^{min} = \left[x_1^{min}, x_2^{min}, \dots, x_n^{min}\right]^T$$

Ψ is an *m*-dimensional vector space of objective functions and defined by Θ and the objective function *f(x)*. $g_j(\vec{x}) \leq 0 (j = 1,2, .., p)$ and $h(\vec{x}) = 0 (j = 1,2, .., q)$ denotes p and q which are respectively the number of inequality and equality constraints. If both *p* and q are equal to zero, then the problem is simplified as an unconstrained optimization problem.

Our tuning method involves an improved multi-objective genetic algorithm (NSGA-II) (K. Deb, 2014). Genetic algorithm is initiated by randomly generated solutions as a population and sorts them into fronts based on non-domination criteria. These solutions are evolved from one generation to another based on the objective evaluation, selection, crossover and mutation operators.

3.5. Evaluation criteria and optimisation variables

The objective functions for our optimisation problem are the accuracy of a model in the prediction of heating and cooling loads. This measure is calculated as the average root mean square (RMSE) for both heating and cooling estimations. When the MOO algorithm generates a population, each solution contains a set of RF parameters. Table 1 summarises these variables.

Table 1RF model hyper-parameters for tuning.

Parameter	Description	Type	Values
n_estimator	The number of trees in the forest.	integer	200 – 1200
max_features	The number of features to consider when looking for the best split:	category	26, 5
max_depth	The maximum depth of the tree	integer	10 – 100
min_samples_split	The minimum number of samples required to split an internal node	integer	2 – 10
min_samples_leaf	The minimum number of samples required to be at a leaf node	integer	1 – 10
bootstrap	Whether bootstrap samples are used when building trees	boolean	True, False

In every generation, solutions are evaluated by training and testing a model over 5000 building records. The train and test procedure is performed using *k*-fold cross-validation. In this procedure, the data is divided into *k* exclusive subsets, and each combination of model parameters and architecture is fitted to each distinct group of $k - 1$ subsets and tested on the remaining subset. This process provides a distribution of errors for a given model choice on different parts of the dataset, i.e., an estimate of the general applicability of the model to represent the variation in the dataset. The average amount of RMSE of *k* folds is then considered as the evaluation measure for each solution.

Table 2 List of input variables for model training of buildings heating and cooling loads

Group	QTY	Stats	Description	Range	Code	Unit
Building	U-value	Average	Average U-value of envelope	0.14–6.06	*uval*	W/m^2 K
	Thermal Mass	Sum	Sum of thermal storage capacity	1e-4–7.61	*tmass*	MWh/K
	Envelope Ratios	Ratio	Ratio of window area to wall area	0.58–85.00	*wwr*	-
			Ratio of window area to floor area	0.01–0.42	*wfr*	-
	Massing	Ratio	Form Factor (Volume / Wall Area)	2.47–17.14	*ff*	-
			Roof Ratio (Roof / Wall Area)	0.31–2.73	*rr*	-
Mixed	Shading	Average	Average sunlit percentage of envelope	0.35–100	*avgsunperc*	%
	Infiltration	Sum	Annual sum of energy gained due to infiltration	0–0.74	*suminfgain*	GWh
			Annual sum of energy lost due to infiltration	−2.7– -1e-4	*suminfloss*	
Other		Sum	Annual sum of Internal Heat Gain	0.03–5.24	*sumIHG*	GWh
Climate	Degree Days	Sum	Annual sum of cooling degree days	(9.6–160)e4	*cdd*	C-day
			Annual sum of heating degree days	424–64878	*hdd*	
	Dry BulbTemp (Hourly)	Avg.	Annual average of dry bulb temperature	−3.11–28.39	*avgtdb*	C
		Median	Median dry bulb temperature	−7.20–30	*medtdb*	
		IQR	Inter-quartile range of dry bulb Temp	3.6–34	*iqrtdb*	
	Dry Point Temp (Hourly)	Avg.	Annual average of dry point temperature	−7.41–21.43	*avgtdp*	C
		Median	Median dew point temperature	−6.4–24.2	*medtdp*	
		IQR	Inter-quartile range of dew point temperature	0–26.8	*iqrtdp*	
	Global Horizontal Irradiation (Hourly)	Avg.	Annual average of global horizontal irradiation	190–509	*avghi*	MWh/m2
		Sum	Annual sum of global horizontal irradiation	0.40–2.23	*sumghi*	
		IQR	Inter-quartile range of global horizontal irradiation	(0.84–5.2)e-3	*iqrghi*	
	Direct Normal Irradiation (Hourly)	Avg.	Annual average of direct normal irradiation	57–676	*avgdni*	MWh/m2
		Sum	Annual sum of direct normal irradiation	−10.34–3.15	*sumdni*	
		IQR	Inter-quartile range of direct normal irradiation	(0.38–26.3)e-4	*iqrdni*	
	Humidity(Hourly)	Avg.	Annual average of relative humidity	22–98	*avrh*	%
		Median	Median relative humidity	18–99.6	*medrh*	

3.6. Description of the datasets

A building dataset simulated using BPS tools is utilised. This data includes 460,000 domestic and non-domestic buildings simulations characterised by 7 structural, 16 climate and 3 mixed features as presented in Table 2. The characteristics of building cases are selected from different sources including, United States Department of Energy commercial building reference database and residential houses in Geneva, Switzerland and north of Germany.

4. Results

The results from the grid search require further investigation to select the best model. Besides, it is not possible to search every potential value for the parameters in the grid due to the size of the huge search space. Therefore, as the hyper-parameters are discretely introduced to the grid, the chance of the optimisation algorithm, which smartly selects the values is higher to reach a model with better accuracy. As expected, the best models from MOO and grid search achieves mean RMSE of 12.56 and 13.68 KW/m2 for heating and 9.28 and 9.43 for cooling predictions, respectively.

Regardless of the obtained accuracy, MOO converged on the selection of the best hyper-parameters 4.5 times faster than the time required for the grid to search the whole space. Considering the average time of 18 seconds for training and test of each fold and the size of possible combinations of the hyper-parameters as almost seven thousand, the grid is completed in 14 days whereas MOO evaluates around 1,500 solutions in 3 days.

The best hyper-parameters providing the most accurate predictions for both heating and cooling loads are as follow: *n_estimators = 337, bootstrap = False, max_depth = 30, max_features = 'sqrt', min_samples_split = 3, min_samples_leaf = 1.*

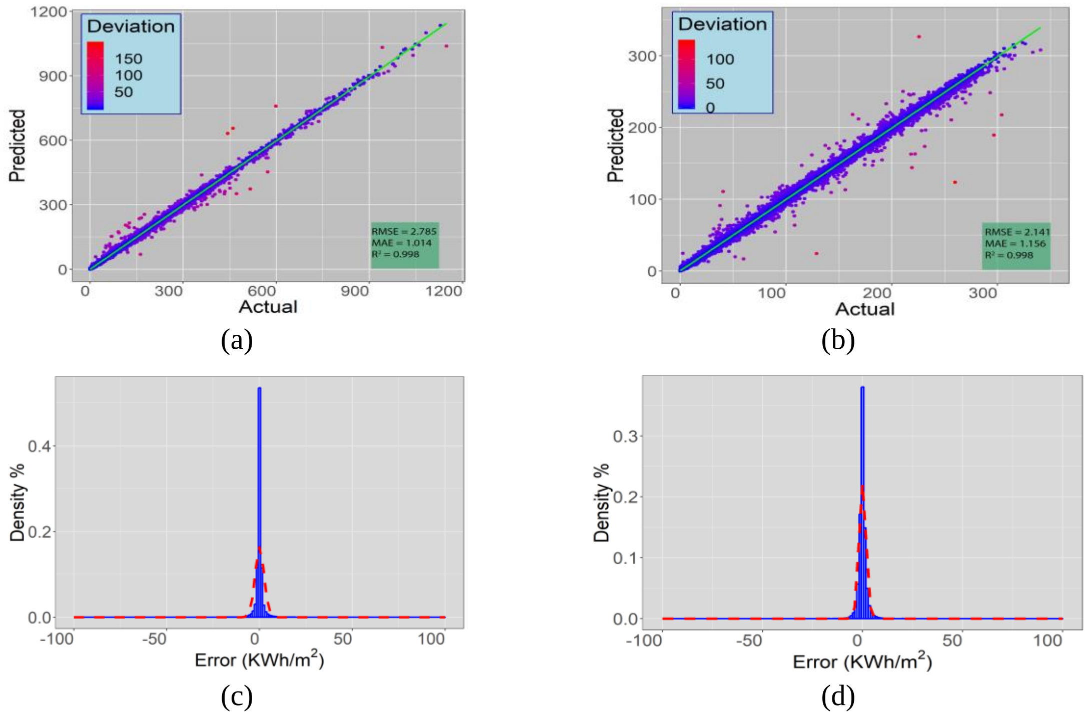


Figure 2: Actual and predicted (a) heating and (b) cooling and (c) and (d) their error distributions, respectively.

After determining RF parameters, a model is then trained and tested with 400,000 building records. The model was fit using 300,000 samples and tested over the rest. Figure 2 illustrates the results as predicted (estimated) loads against loads from the simulator (actual values), and the distribution of errors between simulated-predicted pairs. To investigate the effect of data size on the accuracy of supervised models, mean RMSE of heating and cooling is plotted against the number of train and test records which is depicted in Figure 3. Here, a 10 fold cross- validation is used in the RF model and worst, best and mean

RMSE of all folds are presented. Mean training time is also displayed as the top axis for evaluating computational overhead.

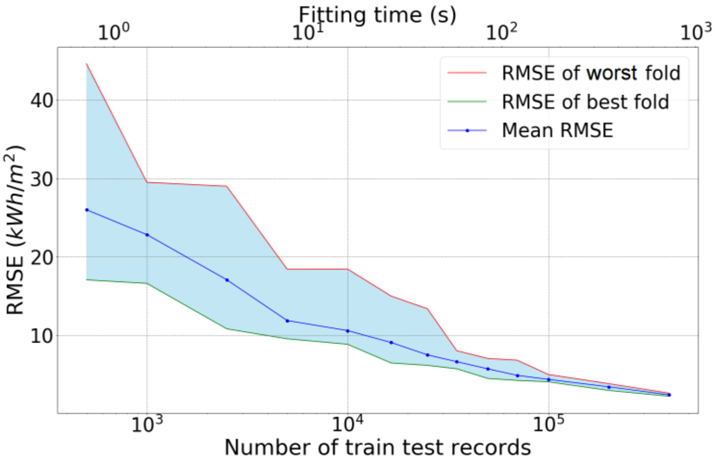


Figure 3: RMSE for heating load against the total number of samples used for training

5. Conclusion

This research addresses the gap in using ML models which require precise tuning to accurately predict building energy loads. As mentioned in the reviewed literature, most research reviewed used MLs without model optimisations, and they proposed to separately model the heating and cooling loads. This paper has proposed a method based on MOO to facilitate the process of selecting hyper-parameters, and simultaneously to optimise the model for both forecasting heating and cooling loads. The proposed approach was evaluated by implementing the random forest decision tree algorithm and testing the accuracy over a building data which was simulated using EnergyPlus. The effectiveness of our proposed approach was demonstrated through comparison with traditional grid search methods. Generating an accurate model for calculation of the energy loads with fast and robust method paves the way for more informed and productive design decisions for built environments. Furthermore, along with the optimisation algorithms, ML also offers a promising solution for efficient retrofit planning of complex buildings, where engineers are not able to carry out massive calculations readily.

Acknowledgements

The research presented in this paper was co-funded by The Data Lab (Edinburgh, UK) and arbnco Ltd (Glasgow, UK), through DataLab SFC Earmarked Grant Agreement: PO DL 00033. This work would also not be feasible without the generous PhD funding for the first author, which was co-funded by the Engineering. The Future scheme from University of University of Strathclyde and the Industry Funded Studentship Agreement with arbnco Ltd (Studentship Agreement Number: S170392-101).

References

Ahmad, M. W., Mourshed, M., & Rezgui, Y. (2017). Trees vs Neurons: Comparison between random forest and ANN for high-resolution prediction of building energy consumption. *Energy and Buildings*, *147*, 77–89.

Chen, Y., & Tan, H. (2017). Short-term prediction of electric demand in building sector via hybrid support vector regression. *Applied Energy*, *204*, 1363–1374. https://doi.org/https://doi.org/10.1016/j.apenergy.2017.03.070

Deb, C., Eang, L. S., Yang, J., & Santamouris, M. (2016). Forecasting diurnal cooling energy load for institutional buildings using Artificial Neural Networks. *Energy and Buildings*, *121*, 284–297.

https://doi.org/http://dx.doi.org/10.1016/j.enbuild.2015.12.050

Deb, K. (2014). Multi-objective optimization. In *Search methodologies* (pp. 403–449). Springer.

Deng, H., Fannon, D., & Eckelman, M. J. (2018). Predictive modeling for US commercial building energy use: A comparison of existing statistical and machine learning algorithms using CBECS microdata. *Energy and Buildings*, *163*, 34–43. https://doi.org/10.1016/j.enbuild.2017.12.031

Dombayci, Ö. A. (2010). The prediction of heating energy consumption in a model house by using artificial neural networks in Denizli-Turkey. *Advances in Engineering Software*, *41*(2), 141–147. https://doi.org/https://doi.org/10.1016/j.advengsoft.2009.09.012

Dong, B., Cao, C., & Lee, S. E. (2005). Applying support vector machines to predict building energy consumption in tropical region. *Energy and Buildings*, *37*(5), 545–553. https://doi.org/https://doi.org/10.1016/j.enbuild.2004.09.009

Hong, S. M., Paterson, G., Mumovic, D., & Steadman, P. (2014). Improved benchmarking comparability for energy consumption in schools. *Building Research and Information*, *42*(1), 47–61. https://doi.org/https://doi.org/10.1080/09613218.2013.814746

Hong, T., Koo, C., Kim, J., Lee, M., & Jeong, K. (2015). A review on sustainable construction management strategies for monitoring, diagnosing and retrofitting the building's dynamic energy performance: Focused on the operation and maintenance phase. *Applied Energy*, *155*, 671–707. https://doi.org/http://dx.doi.org/10.1016/j.apenergy.2015.06.043

Hou, Z., & Lian, Z. (2009). An application of support vector machines in cooling load prediction. In *Intelligent Systems and Applications, 2009. ISA 2009. International Workshop on* (pp. 1–4).

Jain, R. K., Smith, K. M., Culligan, P. J., & Taylor, J. E. (2014). Forecasting energy consumption of multi-family residential buildings using support vector regression: Investigating the impact of temporal and spatial monitoring granularity on performance accuracy. *Applied Energy*, *123*, 168–178. https://doi.org/http://dx.doi.org/10.1016/j.apenergy.2014.02.057

Kalogirou, S. A. (2000). Applications of artificial neural-networks for energy systems. *Applied Energy*, *67*(1–2), 17–35. https://doi.org/10.1016/S0306-2619(00)00005-2

Kalogirou, S., Florides, G., Neocleous, C., & Schizas, C. (2001). Estimation of Daily Heating and Cooling Loads Using Artificial Neural Networks. In *Proceedings of CLIMA 2000 International Conference* (pp. 15–18). Naples: Cyprus University of Technology. Retrieved from http://ktisis.cut.ac.cy/bitstream/10488/883/3/C41-CLIMA2001.pdf

Kalogirou, S., Neocleous, C., & Schizas, C. (1997). Building Heating Load Estimation Using Artificial Neural Networks. In *Proceedings of the 17th international conference on Parallel architectures and compilation techniques* (Vol. 8, pp. 1–8). Retrieved from http://www.inive.org/members_area/medias/pdf/Inive/clima2000/1997/P159.pdf

Khayatian, F., Sarto, L., & Dall'O', G. (2016). Application of neural networks for evaluating energy performance certificates of residential buildings. *Energy and Buildings*, *125*, 45–54. https://doi.org/http://dx.doi.org/10.1016/j.enbuild.2016.04.067

Kialashaki, A., & Reisel, J. R. (2013). Modeling of the energy demand of the residential sector in the United States using regression models and artificial neural networks. *Applied Energy*, *108*, 271–280. https://doi.org/10.1016/j.apenergy.2013.03.034

Li, C., Ding, Z., Zhao, D., Yi, J., & Zhang, G. (2017). Building energy consumption prediction: An extreme deep learning approach. *Energies*, *10*(10), 1525.

Li, Q., Meng, Q., Cai, J., Yoshino, H., & Mochida, A. (2009). Predicting hourly cooling load in the building: A comparison of support vector machine and different artificial neural networks. *Energy Conversion and Management*, *50*(1), 90–96.

https://doi.org/http://dx.doi.org/10.1016/j.enconman.2008.08.033

Li, X., Bowers, C. P., & Schnier, T. (2010). Classification of energy consumption in buildings with outlier detection. *IEEE Transactions on Industrial Electronics*, *57*(11), 3639–3644. https://doi.org/10.1109/TIE.2009.2027926

Massana, J., Pous, C., Burgas, L., Melendez, J., & Colomer, J. (2015). Short-term load forecasting in a non-residential building contrasting models and attributes. *Energy and Buildings*, *92*, 322–330. https://doi.org/10.1016/j.enbuild.2015.02.007

Mena, R., Rodríguez, F., Castilla, M., & Arahal, M. R. (2014). A prediction model based on neural networks for the energy consumption of a bioclimatic building. *Energy and Buildings*, *82*, 142–155. https://doi.org/http://dx.doi.org/10.1016/j.enbuild.2014.06.052

Neto, A. H., & Fiorelli, F. A. S. (2008). Comparison between detailed model simulation and artificial neural network for forecasting building energy consumption. *Energy and Buildings*, *40*(12), 2169–2176. https://doi.org/https://doi.org/10.1016/j.enbuild.2008.06.013

Nikolaou, T., Kolokotsa, D., Stavrakakis, G., Apostolou, A., & Munteanu, C. (2015). Review and State of the Art on Methodologies of Buildings' Energy-Efficiency Classification. In *Managing Indoor Environments and Energy in Buildings with Integrated Intelligent Systems* (pp. 13–31). Springer International Publishing. https://doi.org/https://doi.org/10.1007/978-3-319-21798-7

Papadopoulos, S., Azar, E., Woon, W.-L., & Kontokosta, C. E. (2017). Evaluation of tree-based ensemble learning algorithms for building energy performance estimation. *Journal of Building Performance Simulation*, *1493*, 1–11. https://doi.org/https://doi.org/10.1080/19401493.2017.1354919

Papadopoulos, S., Azar, E., Woon, W.-L., & Kontokosta, C. E. (2018). Evaluation of tree-based ensemble learning algorithms for building energy performance estimation. *Journal of Building Performance Simulation*, *11*(3), 322–332.

Paudel, S., Elmtiri, M., Kling, W. L., Corre, O. Le, & Lacarrière, B. (2014). Pseudo dynamic transitional modeling of building heating energy demand using artificial neural network. *Energy and Buildings*, *70*, 81–93. https://doi.org/10.1016/j.enbuild.2013.11.051

Platon, R., Dehkordi, V. R., & Martel, J. (2015). Hourly prediction of a building's electricity consumption using case-based reasoning, artificial neural networks and principal component analysis. *Energy and Buildings*, *92*, 10–18. https://doi.org/http://dx.doi.org/10.1016/j.enbuild.2015.01.047

Seyedzadeh, S., Rahimian, F. P., Glesk, I., & Roper, M. (2018). Machine learning for estimation of building energy consumption and performance: a review. *Visualization in Engineering*, *6*(1), 5. https://doi.org/https://doi.org/10.1186/s40327-018-0064-7

Seyedzadeh, S., Rahimian, F. P., Rastogi, P., & Glesk, I. (2019). Tuning Machine Learning Models for Prediction of Building Energy Loads. *Sustainable Cities and Society*.

Tsanas, A., & Xifara, A. (2012). Accurate quantitative estimation of energy performance of residential buildings using statistical machine learning tools. *Energy and Buildings*, *49*, 560–567. https://doi.org/https://doi.org/10.1016/j.enbuild.2012.03.003

Wang, Z., Wang, Y., Zeng, R., Srinivasan, R. S., & Ahrentzen, S. (2018). Random Forest based hourly building energy prediction. *Energy and Buildings*, *171*, 11–25. https://doi.org/https://doi.org/10.1016/j.enbuild.2018.04.008

Wong, S. L., Wan, K. K. W., & Lam, T. N. T. (2010). Artificial neural networks for energy analysis of office buildings with daylighting. *Applied Energy*, *87*(2), 551–557. https://doi.org/https://doi.org/10.1016/j.apenergy.2009.06.028

Xuemei, L. X. L., Jin-hu, L. J. L., Lixing, D. L. D., Gang, X. G. X., & Jibin, L. J. L. (2009). Building Cooling Load Forecasting Model Based on LS-SVM. *Asia-Pacific Conference on Information Processing*, *1*, 55–58. https://doi.org/https://doi.org/10.1109/APCIP.2009.22

Yalcintas, M. (2006). An energy benchmarking model based on artificial neural network method with a case example for tropical climates. *International Journal of Energy Research*, *30*(14), 1158–1174. https://doi.org/10.1002/er.1212

Yokoyama, R., Wakui, T., & Satake, R. (2009). Prediction of energy demands using neural network with model identification by global optimization. *Energy Conversion and Management*, *50*(2), 319–327. https://doi.org/10.1016/j.enconman.2008.09.017

Zhao, H.-X., & Magoulès, F. (2012). Feature Selection for Predicting Building Energy Consumption Based on Statistical Learning Method. *Journal of Algorithms & Computational Technology*, *6*(1), 59–77. https://doi.org/10.1260/1748-3018.6.1.59

Zhao, H., & Magoulès, F. (2010). Parallel Support Vector Machines Applied to the Prediction of Multiple Buildings Energy Consumption. *Journal of Algorithms & Computational Technology*, *4*(2), 231–249. https://doi.org/10.1260/1748-3018.4.2.231

Virtual Reality based Facilities Management planning

Simon Swanström Wyke[1]* and Kjeld Svidt[1]
Department of Civil Engineering, Aalborg University
*email: scr@civil.aau.dk

Abstract

Only limited research has been conducted with respect to the use of Virtual Reality for planning of Facilities Management. Through a case study experiment, using only the early stage architectural 3D model of a test building, a Virtual Environment was generated allowing test persons' evaluation of the usability of Virtual Reality as a Facilities Management planning tool. Facilities Management, Building Information Model, Modelling and Management and Virtual Reality are individually widely researched. However, this paper contributes to great amount of scientific literature existing with respect to Facilities Management, by studying the topics in unison. The evaluation of Virtual Reality for Facilities Management planning was divided into a qualitative phase involving interviewing of test persons and a quantitative phase allowing test persons to rate their experience in Virtual Reality in a questionnaire.

The study revealed that 82 per cent of the test persons found Virtual Reality usable as a planning tool for Facilities Management. The experiment evaluation however also showed a wide range of the degree to which the test persons found the tool usable.

Keywords: Virtual Reality (VR), Facilities Management (FM), FM-planning, Building Maintenance

1. Introduction

Facilities Management (FM), Building Information Management (BIM) and Virtual Reality (VR) are topics presently receiving increasing focus in the architectural, engineering and operation industry. FM is by the International Facilities Management Association (IFMA) defined as*: a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating: people, place, processes and technology* (IFMA, 2019). This is also definition used in this paper.

Today, multiple Information and Communication Technology (ICT) tools are used in the FM industry to facilitate management as well as communication and process, people, place and technology integration (Aziz, Nawawi, & Ariff, 2016; IFMA, 2019; Olapade & Ekemode, 2018), and capturing of knowledge through a building's life cycle (Arayici, Onyenobi, & Egbu, 2012; Kymmell, 2008).

Since the introduction of e-mails in the 1970s various types of ICT tools have been developed and introduced to the FM industry such as: Maintenance Management Software, Computer Aided Facilities Management (CAFM) software and Building Information Management (BIM) (Aziz, Nawawi, & Ariff, 2016; Donaldson, 1991; Elmualim & Pelumi-Johnson, 2009; Harrison & Leaman, 1986).

One of the primary motivators for stakeholders in Facilities Management when implementing new technology is the opportunity for direct gains and benefits in their operations (Becerik-Gerber, Jazizadeh, Li, & Calis, 2012). Expanding use of ICT must therefore consider the benefits such can provide the stakeholders.

BIM is defined as either: Building Information Model, Modelling and/ or Management. In this paper we define it as Building Information Management, including both the 3D model, the manipulation of the model and the management/ handling of the model with respect to FM.

Using BIM can provide a way of storing FM data supporting the Facilities Manager during operation (Farghaly, Abanda, Vidalakis, & Wood, 2018; Olapade & Ekemode, 2018) as well as Architectural, Engineering and Construction (AEC) personnel in the early stages of design. Use of BIM additionally allows Facilities Managers to specify what they really need, at early stages of a project development (McAuley, Hore, & West, 2013; Tucker & Masuri, 2018). BIM based FM is sometimes also defined as 6D BIM (Nicał & Wodyński, 2016).

Building Information Management can be beneficial for a variety of FM practices such as commissioning, quality control and assurance, energy maintenance, repair and space management. The model must however be accurate and updated to be usable for FM (Kassem, Kelly, Dawood, Serginson, & Lockley, 2015). Increased control of BIM during design and operation may lead to heightened cost in early project stages, but can potentially reduce the owner's operation and maintenance cost (Becerik-Gerber, Jazizadeh, Li, & Calis, 2012). Facilities Managers are nevertheless hardly involved in BIM (Becerik-Gerber, Jazizadeh, Li, & Calis, 2012; Volk, Stengel, & Schultmann, 2014) or a building's planning process, making maintenance strategies based on "as built" conditions when a building is delivered (Olapade & Ekemode, 2018). FM planning can however, potentially begin before the FM organisation receives an "as built" model, using 3D models from earlier design stages.

VR development has, in recent years, led to increased utilization of the technology (Shi, Du, Lavy, & Zhao, 2016) in many domains (Du, Zou, Shi, & Zhao, 2018; Goulding, Rahimian, & Wang, 2014), as an interactive design platform, supporting collaborative design and co- creation (Petrova, Romanska, Stamenov, Svidt & Lund Jensen, 2017; Rasmussen, Gade, & Jensen, 2017; Svidt & Sørensen, 2012). A tool for simplified communication between building users and designers (Sørensen & Svidt, 2017). Real time audio- visual simulation (Wyke, Christensen, Svidt, & Lund Jensen, 2019). Building evaluation (Kuliga, Thrash, Dalton, & Hölscher, 2015). Simulation of dangerous situations (Wang, Li, Rezgui, Bradley, & Ong, 2014) and user experience testing in a more cost effective way than real life mock- ups (Andrée, Nilsson, & Eriksson, 2016; Zou, Li, & Cao, 2017), with increased control over the tested environment (Kinateder, Müller, Jost, Mühlberger, & Pauli, 2014; Pitt, Goyal, Holt, Ritchie, Day, Simmons, Robinson, Russell, 2005; Wiederhold & Wiederhold, 2010).

Using vendor neutral formats like the industry foundation classes (IFC) allows importing BIM models into CAFM platforms overcoming lack of interoperability between CAFM tolls and the growing number of commercially available BIM packages (Becerik-Gerber, Jazizadeh, Li, & Calis, 2012; Farghaly, K., Abanda, F. H., Vidalakis, C., & Wood, G. 2018). It furthermore allows conversion of geometric data into Virtual Environments (Bille, Smith, Maund, & Brewer, 2014; Rüppel & Schatz, 2011)

To understand how VR can be used by Facilities managers with respect to operation and maintenance, a research study was conducted, using an early stage architectural 3D model (BIM) to generate a Virtual Environment for testing of the usability of VR as a tool for FM- planning.

2. Methodology

In this section, the methods for the qualitative and quantitative data collection are introduced. The description of the technological experimental development is additionally presented and explained.

2.1 Empirical data collection

Empirical data were collected in two phases, using the contextual design method as described by Beyer & Holtzblatt (1997). The first phase involved interviewing facilities management (FM) personnel at Aalborg University's Campus Service (FM-organisation), to attain knowledge of which systems they use in building operation and FM. The second phase involved interviewing test persons, after their participation in a Virtual Reality (VR) experiment. This stage additionally included test persons responding to a questionnaire of six questions, rateable on a scale from 0 to 10.

Eleven test persons participated in the experiment. After immersion into VR for 3-5 minutes, they were asked to evaluate the usability of VR for FM-planning, focussing on building maintenance. The test persons thereafter responded to a questionnaire and an oral interview, documented through audio recording.

Responses from the test persons presented in section: "3. Results" are based on the calculated mean, variance, spread and range of the responses to the questionnaire.

2.2 Technological experimental development

The VR used in the experiment was based on the architectural building model of a selected test building, converted from the .RVT (Autodesk Revit) format into .FBX for generating the Virtual Environment (VE) in 3dSMAX. The generated VE was then exported in .FBX and imported into the Unity Game Engine. The full architectural model was converted into VR; however only a limited area of the building was accessible to the test person in VR during the test, as shown in figure 1. No steps were taken to optimize the VR model to make it more realistic or improved graphically. Only the "raw" architectural model was used, to test if such a model, with low Level of Development (LOD) and lack of technical installations can be used as a FM-planning tool.

The Oculus Developments Kit 2, Head- Mounted Display (HMD) was used in the experiment.

3. Results and Discussion

In this section, the case study and the results from the experiment are presented. All results are discussed promptly after introduction.

3.1 Case study

Aalborg University Campus Service (FM-organisation) is responsible of operating 243.200 square meters of educational facilities in Aalborg, Denmark, owned by the Danish Building and Property Agency (Bygningsstyrelsen), whom in addition to owning the buildings also finance their operation. The FM-organisation is furthermore the primary stakeholders with respect to implementation of new technology (Bygningstyrelsen, 2015), such as VR for FM.

In order to operate and do FM at Aalborg University campus, multiple systems have been implemented, as a combined building operation and FM system, as shown in figure 2. Even though only 2D drawings are used directly as part of the FM-organisations' workflow, 3D models are used as data repositories (Building information management). These models are updated every time changes are made to the facilities portfolio operated by the FM-organisation, in order to be able to generate 2D drawings, which are used in the FM-system.

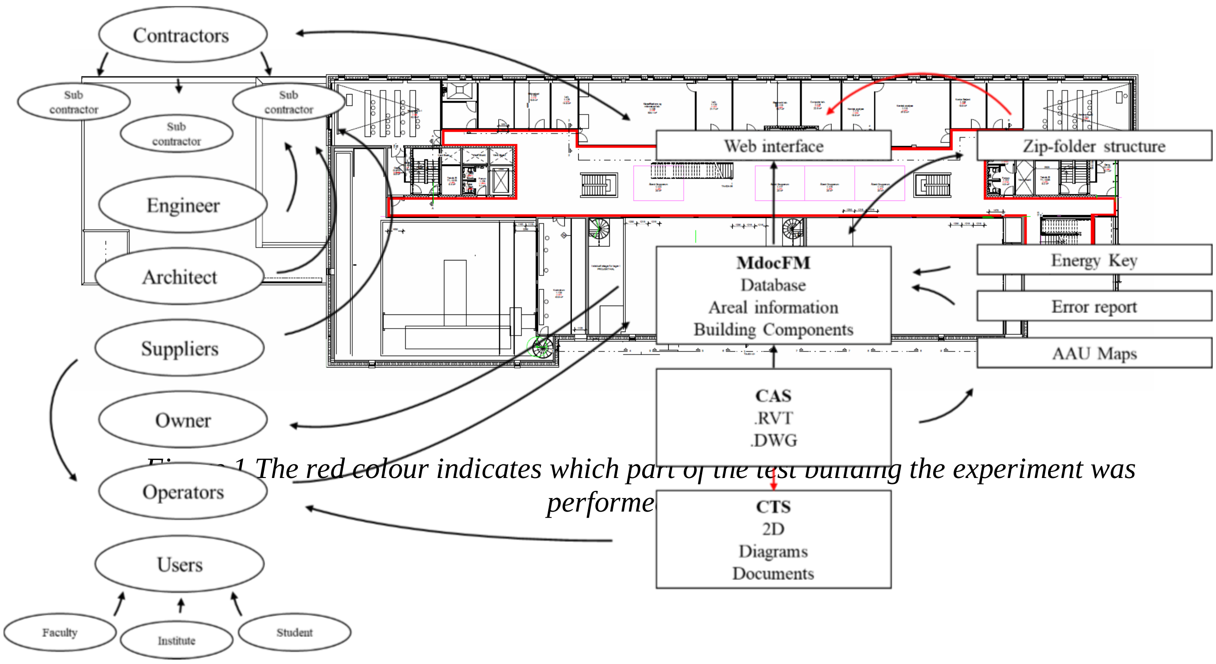


Figure 2 The FM-organization's systems and their interaction with stakeholders. Red arrows indicate manual exchanges.

Since 2011 AAU Campus Service have demanded to receive "as-built models" in the industry foundation classes (IFC) format (AAU Campus Service, 2011), when new buildings are handed over to them for operation. Upon receiving the IFC "as-built" model at building handover the FM-organisation usually re-do the model, to ensure a fitting quality and LOD, as the received models often presents with multiple errors and issues due to an inadequate modelling discipline.

According to a FM-operator: "*One reason for why some models are less usable, is that some building construction projects runs for a very long time, and therefore has many different persons modelling the 3D during the design and construction phase. This change of personnel is displayed in the variation of quality in the models we receive*".

Up to seven different systems are used to fulfil specific purposes, for specific segments of the stakeholders or building users, which is also the case for many other FM-organisations also relying on numerous different systems (Wong, Ge, & He, 2018). The implementation of the seven tools is a result of implementation happening over decades, beginning in the 1970s, as results of new needs arising. Even though combining some of the systems is possible, no efforts are being made in that regard.

One of the primary issues with the workflow the FM-organisation has, is the limited interoperability between systems, which in most situations only allow one-way communication. Even though the use of multiple systems in some cases create internal issues regarding interoperability and difficulties in data exchanges with external partners, the system used by the FM-organisation is capable of providing the data needed to generate and use Virtual Reality.

The FM-organisation only uses 3D model to generate 2D drawings which they use in their building operation and FM. They do however update their 3D models continuously, whenever changes are made to the buildings they operate, allowing for a potential wider use of the models, thus allowing use of VR, without cost involved in modelling the virtual environments.

Adding VR to the system portfolio will undoubtedly increase the complexity of the overall workflow of the FM-organisation By studying if VR can provide benefits in form of heightened understanding and better basis for decision making with respect to FM-planning, it can however be discussed if the increased complexity is overshadowed by the benefits VR can provide.

3.2 Virtual Reality experiment

The Virtual Reality (VR) experiment was designed to asses both common understanding of facilities management (FM) of the test persons and evaluate the usability of VR as a planning tool in FM, using an initial architectural model received from the FM-organisation participating in the case-study to generate the Virtual Environment.

All the participating test persons rated themselves with an average knowledge of facilities management of 4.09 on a scale from 0 to 10, with a spread of the responses of 2.96. As all test persons were professionals in the building industry, the low knowledge average might indicate that there is a need for ways to communicate FM issues generally in the industry. The responses ranged from 3 to 8, indicating that no one was completely unknowing, and that none of the test persons would be considered experts in FM.

When asked how the test persons estimated VR's ability to heighten the understanding of FM needs in the test building, the mean of the responses was calculated as 3.27 with a spread of 2.04. The experiment results showed that use of VR might improve the understanding of the FM needs in a building. However, as the responses ranged from 1 to 5 it was revealed that the test persons only found VR use as what can be interpreted as limited or mediocre at best.

One of the test persons commented on the usability of VR as a FM-planning tool, by stating: *"Maintenance of the high glass areas, is as for my opinion the biggest FM-problem. The inability to clean the windows is clearly visible in the VR model"* - test person A.

For other test persons the limited usability of VR as a FM-planning tool was described as due to low LOD and lack of realism - *"It is a limited model with respect to LOD, but what I noticed is that it is hard to see what is what in the model. It gives a nice overview of the geometry of the building, but that is it. To me it is just a grey model with limited information"* - test person B.

The comment from test person B was elaborated on by test person C stating: *"HVAC and other technical installations would be a nice addition to the model. Except for building geometry, the visibility of FM-issues is limited"* - test person C.

When using initial architectural models of a building for FM-planning, the limitations seem to be the lack of graphic representation of visual capabilities of the building, as well as a lack of technical installations.

Use of HMD to allow immersion into VR, compared to the use of monitor observation of VR, was rated with a mean of 5, however, with a range of the test person responses going from 0 to 9. This indicates that it is highly person depended how HMD enhances perception and tangibleness, making it hard to quantify when HMD-viewed VR can be used beneficially for FM-planning generally.

In the experiment, 82 per cent of test person answered that VR is usable in FM-planning. With respect to VR and the degree of which it be used for FM-planning the mean of the responses was calculated to be 4.09, ranging from 0 to 8. This finding reveals that most people in the experiment saw VR as usable in some way, but without a significant impact as a planning tool. Based on the qualitative responses from the test persons it is however clear that, a more realistic VR regarding colouring and inclusion of technical installations would improve the usability of VR as a FM-planning tool.

Another interesting result from the experiment was the test persons' reaction to the HMD-viewed VR. In the experiment the test persons, rated their experience of VR sickness, with responses ranging from 0 to 10, showing a wide range of reactions to VR. The ratings however showed that 50 per cent of the test persons only had little or no reaction to the HMD-viewed VR, arguing both for and against using the tool as a planning tool.

4. Limitations

- The field of view in a Head- Mounted Display (HMD) is only 100^o (Rift info, 2019), compared to the 210^o horizontal and 150^o vertical view human eyes have (Traquair, 1938), limiting the realism of the experiment.
- Eleven test persons participated in the experiment. All of whom were construction architects, and all participants were male, limiting the generalisability of the experiment results.
- VR sickness is a common consequence in using VR (Feng, González, Amor, Lovreglio, & Cabrera-Guerrero, 2018; Sharples, Cobb, Moody, & Wilson, 2008; Shi, Du, Lavy, & Zhao, 2016; Svidt & Sørensen, 2016), as also indicated in the results from the case study. This limits the use of VR as a FM-planning tool, and the testing of it, as some might not have experienced

the potential of the tool due to feeling uncomfortable.

- Only one FM-organisation participated in this study, and only one scenario was tested in the experiment, making the conclusion on the experiment based on the needs of only one organisation.

5. Conclusion

The case study uncovered that even though architectural models are handed over to an FM-organisation, they are not necessarily used to improve understanding of issues or included in the planning of Facilities Management. They can nevertheless be converted into Virtual Reality (VR), and provide benefits without any significant financial impact on the FM-organisation, with respect to generating the Virtual Environment.

The study revealed that using the initial architectural design model for Facilities Management planning can provide a better understanding, when presented in VR. The improvement of understanding is however highly depended on:

1) The visual representation of the building in VR.
2) The Level of Development of the model used for generating VR.
3) Who are using VR?

50 per cent of the test persons experienced no or limited VR sickness during the experiment, making it hard to conclude to what degree VR sickness limits the use of VR viewed through a Head Mounted Display (HMD) when used for Facilities Management planning.

Future work

Future work will include testing the use of Virtual Reality with a bigger group of test persons allowing a more generalizable foundation for conclusion with respect to usability in Facilities Management planning.

Future work will additionally include testing of multiple scenarios and test buildings, from different stages of the building design, including “as built” models. This will make it possible to conclude when in the design phase 3D models have the best degree of information and visual development for planning of Facilities Management.

Acknowledgements

The authors would like to thank Aalborg University’s Campus Service and the experiment participators and extend our gratitude to the COWI foundation for financing parts of this research.

References

AAU Campus Service. Afleveringsansvarlig ProjektID : Byggesag : IKT-teknisk afleveringsspecifikation (2011). Retrieved from https://www.campusservice.aau.dk/ digital Assets/126/126789_29694_ikt-teknisk_afleveringsspecifikation.pdf

Andrée, K., Nilsson, D., & Eriksson, J. (2016). Evacuation experiments in a virtual reality high-rise building: exit choice and waiting time for evacuation elevators. *Fire and Materials*, *40*(4), 554–567. https://doi.org/10.1002/fam.2310

Arayici, Y., Onyenobi, T., & Egbu, C. (2012). Building Information Modelling (BIM) for Facilities Management (FM). *International Journal of 3-D Information Modeling*, *1*(1), 55–73. https://doi.org/10.4018/ij3dim.2012010104

Aziz, N. D., Nawawi, A. H., & Ariff, N. R. M. (2016). ICT Evolution in Facilities Management (FM): Building Information Modelling (BIM) as the Latest Technology. *Procedia - Social and*

Behavioral Sciences, *234*, 363–371. https://doi.org/10.1016/j.sbspro.2016.10.253

Becerik-Gerber, B., Jazizadeh, F., Li, N., & Calis, G. (2012). Application Areas and Data Requirements for BIM-Enabled Facilities Management. *Journal of Construction Engineering and Management*, *138*(3), 431–442. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000433

Beyer, H., & Holtzblatt, K. (1997). *Contextual design: defining customer-centered systems*. Elsevier Science & Technology.

Bille, R., Smith, S. P., Maund, K., & Brewer, G. (2014). Extending Building Information Models into Game Engines. *Proceedings of the 2014 Conference on Interactive Entertainment - IE2014*, 1–8. https://doi.org/10.1145/2677758.2677764

Bygningstyrelsen. (2015). Helhedsplan for Aalborg Universitet 2015 - 2021, (December). Retrieved from https://www.bygst.dk/media/413077/Helhedsplan-AAU.pdf

Donaldson, I. (1991). The Scope of Computer Aided Facilities Management: Part I. *Facilities*, *9*(11), 5–11. https://doi.org/10.1108/EUM0000000002164

Du, J., Zou, Z., Shi, Y., & Zhao, D. (2018). Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making. *Automation in Construction*, *85*(October 2017), 51–64. https://doi.org/10.1016/j.autcon.2017.10.009

Elmualim, A., & Pelumi-Johnson, A. (2009). Application of computer-aided facilities management (CAFM) for intelligent buildings operation. *Facilities*, *27*(11/12), 421–428. https://doi.org/ 10.1108/02632770910980718

Farghaly, K., Abanda, F. H., Vidalakis, C., & Wood, G. (2018). Taxonomy for BIM and Asset Management Semantic Interoperability. *Journal of Management in Engineering*, *34*(4), 04018012. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000610

Feng, Z., González, V. A., Amor, R., Lovreglio, R., & Cabrera-Guerrero, G. (2018). Immersive virtual reality serious games for evacuation training and research: A systematic literature review. *Computers and Education*, *127*(September), 252–266. https://doi.org/10.1016/j.compedu. 2018.09.002

Goulding, J. S., Rahimian, F. P., & Wang, X. (2014). Virtual reality-based cloud BIM platform for integrated AEC projects. *Journal of Information Technology in Construction*, *19*(August 2013), 308–325.

Harrison, A., & Leaman, A. (1986). Computerised facilities management systems. *Facilities*, *4*(6), 13–14. https://doi.org/10.1108/eb006365

IFMA. (2019). What is FM - Definition of Facility Management. Retrieved January 29, 2019, from https://www.ifma.org/about/what-is-facility-management

Kassem, M., Kelly, G., Dawood, N., Serginson, M., & Lockley, S. (2015). BIM in facilities management applications: a case study of a large university complex. *Built Environment Project and Asset Management*, *5*(3), 261–277. https://doi.org/10.1108/BEPAM-02-2014-0011

Kinateder, M., Müller, M., Jost, M., Mühlberger, A., & Pauli, P. (2014). Social influence in a virtual tunnel fire - Influence of conflicting information on evacuation behavior. *Applied Ergonomics*, *45*(6), 1649–1659. https://doi.org/10.1016/j.apergo.2014.05.014

Kuliga, S. F., Thrash, T., Dalton, R. C., & Hölscher, C. (2015). Virtual reality as an empirical research tool - Exploring user experience in a real building and a corresponding virtual model. *Computers, Environment and Urban Systems*, *54*, 363–375. https://doi.org/10.1016/j.compenvurbsys. 2015.09.006

Kymmell, W. (2008). *Building information modeling : planning and managing construction projects with 4D CAD and simulations* (6th ed.). New York: McGraw-Hill : Print. Retrieved from https://www.worldcat.org/title/building-information-modeling-planning-and-managing-construction-projects-with-4d-cad-and-simulations/oclc/191898180?page=citation

Mcauley, B., Hore, A. V, & West, R. (2013). Establishing Key Performance Indicators to Measure the Benefit of Introducing the Facilities Manager at an early Stage in the Building Information Modelling Process Establishing Key Performance Indicators to measure the benefit of introducing the Faciliti, *2*(December), 61–69. https://doi.org/10.4018/ij3dim.2013100104

Nicał, A. K., & Wodyński, W. (2016). Enhancing Facility Management through BIM 6D. *Procedia Engineering*, *164*(June), 299–306. https://doi.org/10.1016/j.proeng.2016.11.623

Olapade, D. T., & Ekemode, B. G. (2018). Awareness and utilisation of building information modelling (BIM) for facility management (FM) in a developing economy. *Journal of Facilities Management*, *16*(4), 387–395. https://doi.org/10.1108/JFM-09-2017-0046

Petrova, E., Romanska, I., Stamenov, M., Svidt, K., & Lund Jensen, R. (2017). Development of an Information Delivery Manual for Early Stage BIM-based Energy Performance Assessment and Code Compliance as a Part of DGNB Pre-Certification. *Proceedings of the 15th International Conference of the International Building Performance Simulation Association*, 2100--2109. https://doi.org/10.26868/25222708.2017.556

Pitt, M., Goyal, S., Holt, P., Ritchie, J., Day, P., Simmons, J., Robinson, G., Russell, G. (2005). An innovative approach to facilities management in the workplace design brief. *Facilities*, *23*(7/8), 343–355. https://doi.org/10.1108/02632770510600290

Rasmussen, M., Gade, A. N., & Jensen, R. L. (2017). Bridging the Gap between Actors and Digital tools in a Knotworking Design Process. *When Social Science Meets BIM and LEAN (Vol. 1, Chapter 5, Pp. 3)*, (January), 1–7.

Rift info. (2019). Oculus Rift Specs - DK1 vs DK2 comparison. Retrieved April 23, 2019, from https://riftinfo.com/oculus-rift-specs-dk1-vs-dk2-comparison

Rüppel, U., & Schatz, K. (2011). Designing a BIM-based serious game for fire safety evacuation simulations. *Advanced Engineering Informatics*, *25*(4), 600–611. https://doi.org/10.1016 /j.aei.2011.08.001

Sharples, S., Cobb, S., Moody, A., & Wilson, J. R. (2008). Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems. *Displays*, *29*(2), 58–69. https://doi.org/10.1016/j.displa.2007.09.005

Shi, Y., Du, J., Lavy, S., & Zhao, D. (2016). A Multiuser Shared Virtual Environment for Facility Management. *Procedia Engineering*, *145*, 120–127. https://doi.org/10.1016/j.proeng.2016.04.029

Sørensen, J. B., & Svidt, K. (2017). BIM-based Multiuser Collaborative Virtual Environments. In A. Fioravanti & S. Cursi (Eds.) (Vol. 1, pp. 111–118). Rome: eCAADe. https://doi.org/978-94-91207-12-9

Svidt, K., & Sørensen, J. B. (2012). Development of a Virtual Reality Solution for End User Involvement in Interior Design. *ECAADe: Conferences*, *2*, 541–546.

Svidt, K., & Sørensen, J. B. (2016). Development of a Virtual Reality Solution for End User Involvement in Interior Design. *ECAADe: Conferences*, *2*, 541–546.

Traquair, H. M. (1938). *An Introduction to Clinical Perimetry*. London.

Tucker, M., & Masuri, M. R. A. (2018). The development of facilities management-development process (FM-DP) integration framework. *Journal of Building Engineering*, *18*(November 2017), 377–385. https://doi.org/10.1016/j.jobe.2018.04.007

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings - Literature review and future needs. *Automation in Construction*, *38*, 109–127. https://doi.org/10.1016/j.autcon.2013.10.023

Wang, B., Li, H., Rezgui, Y., Bradley, A., & Ong, H. N. (2014). BIM based virtual environment for fire emergency evacuation. *Scientific World Journal*, *2014*. https://doi.org/10.1155/2014/589016

Wiederhold, B. K., & Wiederhold, M. D. (2010). Virtual Reality Treatment of Posttraumatic Stress Disorder Due to Motor Vehicle Accident. *Cyberpsychology, Behavior, and Social Networking*, *13*(1), 21–27. https://doi.org/10.1089/cyber.2009.0394

Wong, J. K. W., Ge, J., & He, S. X. (2018). Digitisation in facilities management: A literature review and future research directions. *Automation in Construction*, *92*(March), 312–326. https://doi.org/10.1016/j.autcon.2018.04.006

Wyke, S. S., Christensen, F., Svidt, K., & Lund Jensen, R. (2019). Realistic Real Time Simulation of Room Acoustics using Virtual Reality with Auralization. In Proceeding of *eCAADe RIS 2019*.

Zou, H., Li, N., & Cao, L. (2017). Emotional Response–Based Approach for Assessing the Sense of Presence of Subjects in Virtual Building Evacuation Studies. *Journal of Computing in Civil Engineering*, *31*(5), 04017028. https://doi.org/http://dx.doi.org/10.5336/medsci.2009-11027

Video Content Analysis-Based Detection of Occupant Presence for Building Energy Modelling

Ipek Gursel Dino[1 2, *], Esat Kalfaoglu[1], Alp Eren Sarı[1], Sahin Akin[1], Orcun Koral Iseri[1],

A. Aydın Alatan[1], Sinan Kalkan[1], Bilge Erdogan[2]

[1] Center for Image Analysis (OGAM), Middle East Technical University, Turkey

[2] Department of Architecture, Middle East Technical University, Turkey

[2] Heriot-Watt University, United Kingdom

*email: ipekg@metu.edu.tr

Abstract

The information on occupant presence plays a critical role in building energy modeling for spaces with a high number of occupants. A thorough understanding of occupant behavior is key to precise Building Energy Modeling (BEM) and to increase the precision of the simulation results. Capturing occupant-related information is difficult due to its stochastic and temporally uncertain nature. In this paper, we propose a robust video content analytical approach for the fast and accurate analysis of temporal and spatial video content. This approach counts the number of occupants in a classroom in an existing building by processing the recordings of video cameras. Two novel counting methods were implemented. The first, namely the Average Counting Method, uses cameras installed in the room directed in different angles, this method relies on detecting and counting occupant heads using a deep convolutional network, namely YOLOv2, that we trained on an existing head dataset. The second method, namely the Entrance Counting Method, uses cameras directed towards the room entrance and increments or decrements a counter based on the occupants entering and exiting the classroom. In addition to YOLOv2, the Discriminative Correlation Filter with Channel and Spatial Reliability (CSR-DCF) was used to create temporal relationships. At the same time, the ground truth was established by manual head counting. The analysis of the results of the one-week recordings initially indicate occlusion problems for the videos of door cameras in case of crowded groups. The videos of room cameras also experienced similar difficulties due to occlusions and the detection of occupants located further from the cameras. Based on these observations, an approach to combine the calculations of both methods is developed, wherein the room cameras are considered as the reference in case of local minima, while the rest is calculated using door cameras with respect to these references. Finally, we validate our approach through two experiments. The first experiment concerns the quantitative comparison between the proposed approach and the ground truth acquired through manual counting methods. The second experiment evaluates the results of the proposed approach in an energy model by quantifying the degree of change in terms of different metrics concerning building energy performance. The results are indicative of the critical role of occupancy in energy modeling.

Keywords: computer vision, deep learning, video content analysis, building occupancy, building energy modeling and simulation

1. Introduction

Building retrofit necessitates energy simulation tools to quantify energy performance and occupant comfort measures. Building energy demand is largely determined by two main data categories. The physical data includes aspects related to the climate, building envelope, building services and energy systems, while the occupant-related data relates to the number of occupants, their activities and behavior in building spaces (O'Brien et al., 2017). The second occupant-related category is significant for energy modeling, as occupants contribute to internal heat gains and emit pollutants such as carbon dioxide, thereby changing the indoor environment (Labeodan et al., 2015). Occupants also adapt the physical building conditions to improve comfort, such as adjusting lighting, heating/cooling set points, curtains, therefore observation becomes complex (Day et al., 2012; Schweiker et al., 2017). Occupant presence is considered as critical, as it has a substantial influence on building resource use and indoor environmental quality, i.e. thermal comfort, ventilation, lighting (Lam, 2015; Toftum, 2010). However, occupant-related information is difficult to capture due to its stochastic and temporal nature (Reinhart C. F. & K., 2003; Yoshino et al., 2017). The most common approach to represent occupancy presence is "diversity profiles". Standard templates using long-term observational data from different buildings and space types are common; however, they run the risk of neglecting the temporal variations, such as seasonal habits, differences in behavior between weekdays and atypical and unpredicted occupant behavior, especially in crowded places (Hong et al., 2017; Kelly Seryak & Kissock, 2003).

Various occupancy sensing technologies have been developed to accurately quantify occupant presence, including in-situ measurements, laboratory experiments (simulating the process) and surveys (Agency, 2018). Between these options, real-time time data collection is effective in order to obtain both regular patterns and extraordinary situations (Gilani et al., 2017). However, choosing the right tool for in-situ measurement is crucial, for instance, Passive Infrared Motion detectors (PIR) are dependent on occupant motion and they only provide presence or absence information rather than the number of people (Amin et al., 2008). On the other hand, the use of proxy measurements through environmental sensor networks is a rather recent research area, but they also require a comprehensive sensor infrastructure (i.e. CO2, CO, TVOC, small particulates, motion, temperature, humidity) and sensor calibrations (Akkaya et al., 2015; Hoes et al., 2009). A robust alternative can be implemented using computer vision methods, such as real-time camera monitoring (Duarte et al., 2013). There is much potential in the use of video cameras for data collection and advanced video analysis for the fast and accurate analysis of temporal and spatial video content (Dziedzic et al., 2017; Sarkar et al., 2008). Related, data can be easily connected with camera registration during the specified period than occupancy information derived by using human detection algorithms (Benezeth et al., 2011; Han & Bhanu, 2007). The collected data of cameras represents a realistic pattern that is also suitable for building energy simulations after converting to a fraction based schedule framework. As in this research aims to obtain, camera monitoring can control occupant presence and occupant activity simultaneously. However, detecting and tracking people remain as challenging problems in complex scenes with multiple people, occlusions and clutter (Andriluka, 2008). This paper presents a method that counts the number of people in a room from video recordings using automated content analysis.

2. Methodology

The proposed method aims to estimate the number of people in an indoor environment from video recordings. The results are registered in 10-minute intervals for a duration of one week, which is to be provided as an input to the energy simulation model. The method primarily uses a head detection algorithm. Supportive tools are background modeling and tracking algorithms. There are two different approaches to estimate the number of people considered in this work. The first approach, the average counting method, averages the number of detected heads per frame for the representation of a determined time interval. The second approach, the entrance counting method, counts the heads entering and exiting the room through the door. It is observed that one can outperform another depending on the specific physical conditions in the room. Therefore, a novel hybrid approach is developed, to acquire a more reliable prediction considering these situations.

2.1 Vision Techniques Used in the Algorithm

In this section, three machine vision tools that are used in the proposed methods are explained. The first tool is the head detection algorithm that is used to estimate the count of people at an instant. The second tool is background modeling, which aims to reduce the number of false candidates given by the head detection algorithm. The third tool is tracking, which creates the temporal relationship between the frames and aims to find the missing detections of the head detection algorithm.

Head Detection

Head detection is implemented via the well-known object detection algorithm "You Look Only Once v2" (YOLOv2 or YOLO9000) in the literature (Redmon & Farhadi, 2017). Among the existing methods in the literature, such as Faster R-CNN and Single Shot Detector (SSD), YOLOv2 has proven to outperform others regarding speed and accuracy (Liu et al., 2016; Ren et al., 2017). YOLOv2 algorithm predicts object categories and locations simultaneously. In this algorithm, the image is divided into a grid. Every grid cell is checked for whether an object exists in it or not. For each grid cell, there are five *anchor boxes*, which are specialized for objects of various sizes. Each anchor box is used to estimate the location and the size of the objects. The size of the grid is an important parameter because only one object can be detected per grid. To capture the very distant people and to increase the grid size, we trained the network with 1280x1280 pixel images for the average counting method and 736x736 for the entrance counting method (the original implementation of YOLOv2 was trained with 416x416 pixel images). Moreover, to overcome the problems of overfitting during training, which results in the inability of the model to generalize, a uniform scale between 1.0 and 1.1 is selected and the images are randomly cropped.

Background Modeling (Background Subtraction)

While counting people, head detection is preferable over the face or the whole body. This is because people may not be directly facing the camera, which is problematic for face detection. Another problem is that the whole body is typically susceptible to occlusion in crowded rooms. On the other hand, head detection can be equally challenging since heads are not as distinguishable as faces or whole bodies. Owing to this, objects such as curved chairs, backpacks or even the backs of people can be misclassified as heads.

Background modeling offers a solution to this problem by distinguishing moving objects (humans) against a static background for a given frame. In this study, the Mixture of Gaussian 2 (MOG2) approach is implemented, where every pixel is represented with a Gaussian Mixture Model (GMM) (Zivkovic & Van Der Heijden, 2006). There is a maximum number of N mixtures of Gaussian color clusters and the instantaneous number of clusters are determined adaptively, such that the clusters that are rarely seen are ignored. Since GMM models the background, the components with a higher probability in the data tend to be part of the background. An update coefficient, or the learning rate of the algorithm, is selected as a small value, such that a foreground object is still identified as part of the foreground for approximately one minute even when it is motionless. This is to eliminate the possibility that motionless people are identified as background by the algorithm. The flowchart showing the combined implementation of head detection with background modeling can be found in Figure 1. The head candidates are eliminated if the area of boxes of head candidates is less than one percent of the total image area. To clarify the head candidate elimination, every head candidate has a bounding box to represent the head which is shown in Figure 1. Background modeling block produces a mask in which white pixels represent the foreground regions and black pixels represent the background regions which is also shown in Figure 1. For the corresponding pixels of the bounding box in the mask, if the ratio of a number of foreground pixels to the number of total pixels is less than one percent, the head candidate which has that bounding box is eliminated. These filtered head candidates are called as foreground head candidates.

Tracking

Tracking is used to increase the probability of a head being detected in consecutive frames. In the proposed algorithm, it is only used in the entrance counting method. The reason for not using tracking in average counting method is that there are too many heads to track in this method and the complexity of good trackers is linearly increasing with the number of objects tracked.

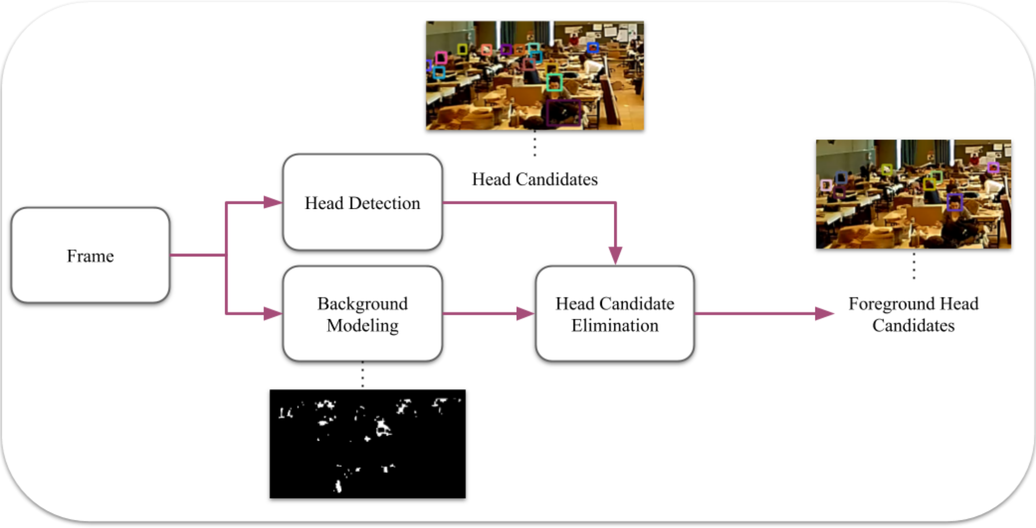


Figure 1: Head Detection with Background Modeling

Recently, the correlation-based trackers have been receiving attention because of the joint consideration of speed and performance. For our algorithm, we consider three types of correlation-based trackers, that are Kernelized Correlation Filters (KCF), Background-Aware Correlation Filters (BACF) and Discriminative Correlation Filter Tracker with Channel and Spatial Reliability (CSR-DCF) (Galoogahi et al., 2017; Henriques et al., 2015; Lukežič et al., 2018). While KFC is the fastest among all, it has the lowest performance and is susceptible to the change in the head's scale, and therefore it loses the head track very easily in our case. According to TrackingNet, CSR-DCF shows higher performance while BACF is faster (Müller et al., 2018). However, the OpenCV 3.4.2 implementation of CSR-DCF seems to be much faster from the original BACF. For the head detection problem, several scenarios are investigated and it is observed that there is not a significant performance difference between them. Therefore, CSR-DCF is selected due to its speed and ease of implementation.

The Intersection Over Union (IOU) measure is used to establish the connection between the frames. However, to tackle the problems of the change of head sizes in the head detection algorithm, we propose a modification to IOU, in that the area of intersection of the two boxes is divided by the area of the smaller box, instead of the area of union. The boxes of foreground head candidates (see Figure 1) from the previous frame are tracked and compared with the boxes of foreground head candidates of the upcoming frame. If the IOU values of the box pairs exceed a certain threshold, they are assumed to belong the same head. If an IOU value is below the threshold, this means that, in the upcoming frame, the head detection failed to detect the head. Therefore, the tracked missing heads are also added to the list of found heads of the upcoming frame.

2.2 Proposed Person Counting Approaches

In this section, three different approaches have been proposed to estimate the number of people in the classroom by using the tools explained above. These are (i) the average counting method that takes the average of the people count from the related frames, (ii) the entrance counting method that counts the entering and exciting people from the entrance of the classroom and (iii) the combined counting method, which is a hybrid of the average counting method and entrance counting method.

The Average Counting Method

The flow diagram of the average counting method can be seen in Figure 2. The algorithm counts the number of heads frame by frame. The average of all the counts estimates the number of people in the environment.

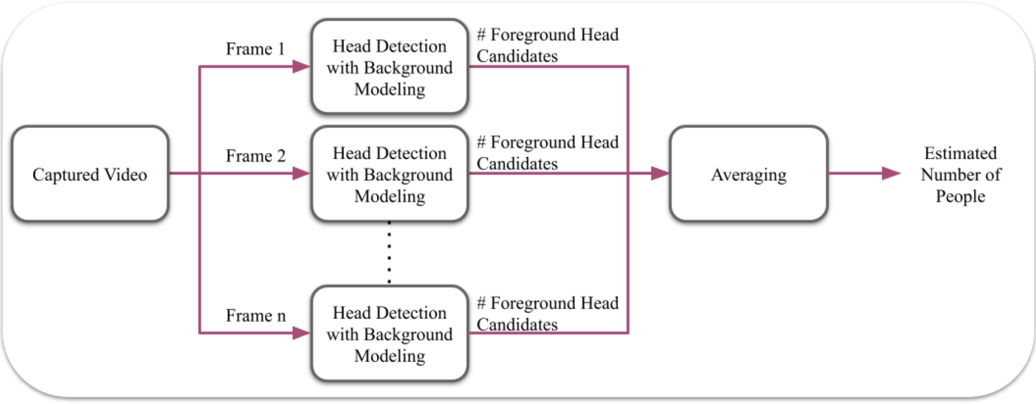


Figure 2: Average Counting Method

For this method, we experimented with the videos of the cameras installed in the classroom (see Section 3). To be able to visually cover the whole room, four cameras are used such that every camera is responsible for a fixed region of the room (see Figure 4). This results in some undesired intersections between the regions because of the projection of the world to the camera scene. From the videos, only every nth frames are considered. This n value is changed to 1, 3, 5 and 10 and it is observed that there is not a significant change in performance.

The Entrance Counting Method

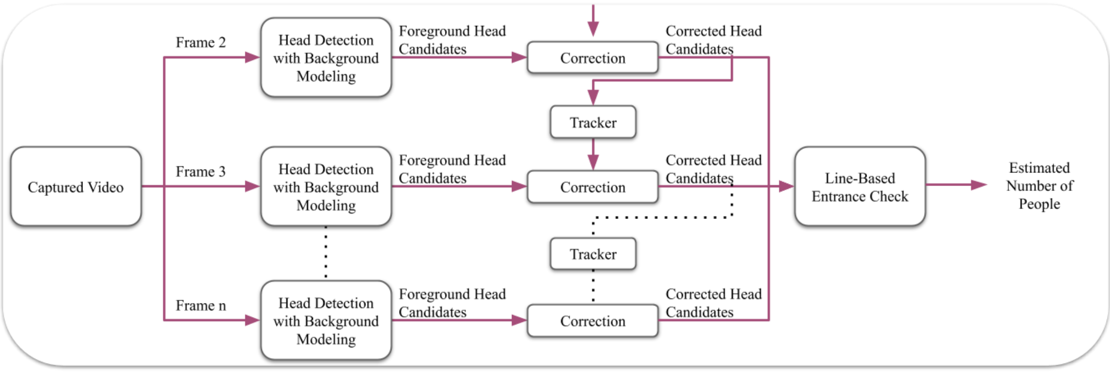


Figure 3: Entrance Counting Method

The entrance counting method counts the people entering and exiting the room through the door. An important difference between this method from the average counting method is that it includes a tracker in order to introduce temporal information into the algorithm. The flow diagram of the method can be seen in Figure 3. The correction process seen in the figure is the method that combines the head candidates of the upcoming frame with the tracked heads of the previous frame (see Section 2.1 for details). The entering and exiting people are counted with a basic *line* approach. If the center of a head passes from one side of the line to the other side, the head is assumed to enter or exit the environment.

There are three cameras used in this method. The average counts of these three cameras yield the estimate of the number of people in the room. As a side note, in order to deal with the detection of backs of the people which may yield to a double count for a person, thresholds on the size of the boxes of the head candidates are applied differently for every door camera and these are determined by visual experiments.

The Combined Counting Method (CCM)

From the tests, it is observed that the average counting method and the entrance counting method can outperform one another in different circumstances. The average counting method is prone to occlusion and image resolution due to long camera distances whereas the entrance counting method works better when people enter the classroom one person at a time. However, its performance is drastically affected by severe occlusions, especially in cases of large numbers of people exiting the classroom at once. Therefore, we combine these two methods in CCM in such a way that they are alternately used when required. In this combined method, the algorithm starts with the entrance counting method. In case of severe occlusions at the entrance, the average counting method takes over. When the method detects an increasing trend in the people count, the combined method switches back to the entrance counting method and takes the reference of people to count from the average counting method. As such, the algorithm switches back and forth between the two methods to complement each other.

3. Experiment Results

This section presents the results concerning the proposed occupant counting method. In particular, we propose two different experiments. Experiment 1 concerns a quantitative comparison between the proposed approach, the standard occupancy templates and the ground truth. In Experiment 2, we evaluate the results of the proposed approach in an energy model and quantify the degree of change in terms of different metrics concerning building energy performance.

3.1 Experiment setup and dataset

The cameras used in this work are IP cameras with 1280x720 resolution at 10 fps, 130° camera angle, and H.264 video encoding. The cameras record videos only when motion is detected and are directly uploaded to the Amazon cloud services. Seven cameras were installed in a classroom of 331 m^2, three of which are pointed at the door (door cameras), while the other four are pointed at the classroom (room cameras) as can be seen in Figure 4. The door cameras are used for the entrance counting method. The classroom is used as a design studio for an architecture department, where a high number of people and unusual occupancy patterns are expected due to the students' prolonged study hours. The proposed method was used for person counting during the same week. Videos were recorded for a duration of a week (24-30 December 2018). The results were registered in a resolution of 10 minutes, and are timestamped in data sheets.

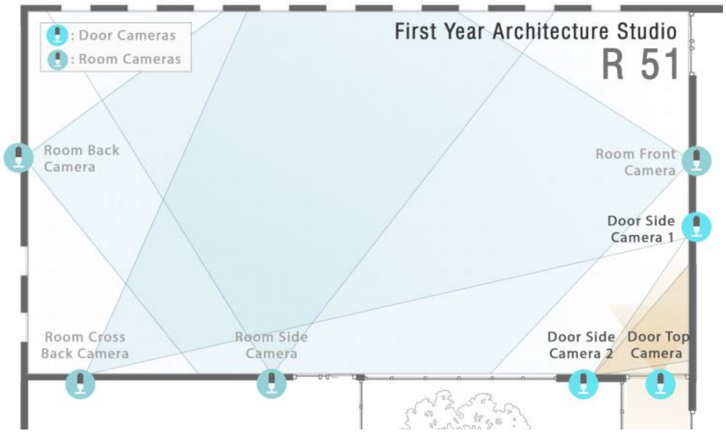


Figure 4: The plan layout of the classroom showing the cameras

The dataset used in this project is SCUT-HEAD which is a large-scale head detection dataset and contains 2000 images with 67321 annotated heads from the same class environment and same camera angle and 2405 images with 43930 annotated heads which are crawled from the Internet (Peng et al., 2018). In addition, 535 images from the test environment in this work were added to the dataset. Approximately 200 of 535 images that do not contain people or heads were added as negative samples. This aims to make sure that the system performs better at ignoring objects that appear like heads, such as curvy-shaped chairs and backpacks.

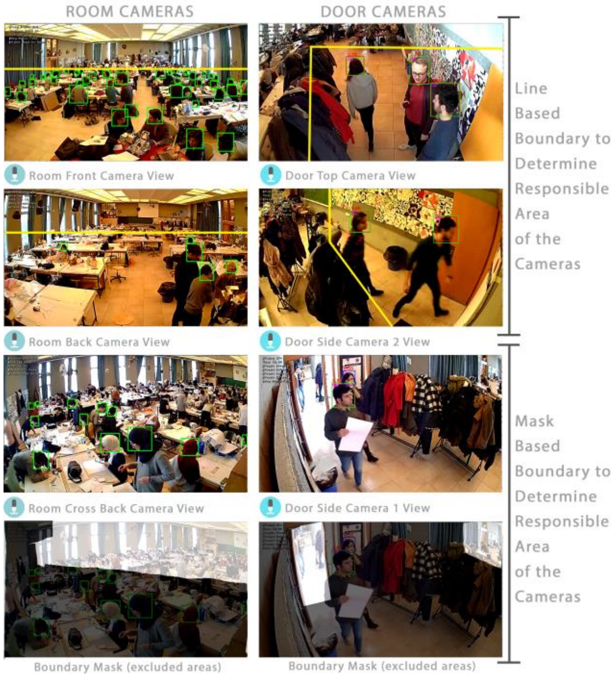


Figure 5: Views of the classroom under different camera angles

3.2 Results for Experiment 1

In Experiment 1, the proposed approach is benchmarked against two ground truth measurements manually recorded during the first day of the video recordings (24 December, from 9:30 AM to 6:30 PM) every 30 minutes. The first was In-Situ Measurement (ISM), where the people in the classroom were manually counted by a person in the room. ISM isn't completely reliable, as it was not possible to control the human movement or new people entering the classroom during the counting process. The second was Video Recording Measurements (VRM), where people were manually counted from the video recordings for the same day, therefore inheriting the occlusion and human recognition problems in the proposed algorithm.

The results can be found in Figure 6 and Table 1. We notice that although the trends are similar, there are some discrepancies between the measurement results, largely due to the fact that the reference point is taken from the average counting method. Therefore, even if the entrance counting method were very precise, the error in the reference point would still exist in the system and result in an offset. For both ground truth measurements in Table 1, it is observed that some of the high percentage errors are caused by mass exiting from the door at the end of the class, i.e. at 12.30PM and 5.30PM. This is observed to be due to the fact that the algorithm does not switch to the average counting method on time. Another reason for high percentage errors stems from the cases with a few numbers of people being present in the environment. For example, at 9.30AM, while the error is very low (3 people), the percentage error appears to be 30%.

Table 1. Comparative analysis between the two ground truth measurements and the proposed approach

Time	In-situ measurement (ISM)	Video recording measurement (VRM)	Combined Counting Method (CCM)	Percentage Error (ISM vs. CCM)	Percentage Error (VRM vs. CCM)
9:30	9	10	11.66	29.56	16.60
10:00	10	11	11.86	18.60	7.82
10:30	19	25	23.00	21.05	8.00
11:00	116	92	111.00	4.31	20.65

11:30	125	95	110.00	12.00	15.79
12:00	115	105	119.00	3.48	13.33
12:30	30	28	34.60	15.33	23.57
13:00	35	33	36.00	2.86	9.09
13:30	58	62	56.53	2.53	8.82
14:00	101	86	97.00	3.96	12.79
14:30	98	86	98.66	0.67	14.72
15:00	103	95	108.00	4.85	13.68
15:35	106	92	105.40	0.57	14.57
16:00	111	98	111.40	0.36	13.67
16:30	114	108	116.00	1.75	7.41
17:00	118	103	120.00	1.69	16.50
17:30	35	32	21.60	38.29	32.50
18:00	19	24	18.50	2.63	22.92
18:30	16	15	16.86	5.38	12.40
Average	70.42	63.16	69.85	0.82	10.59

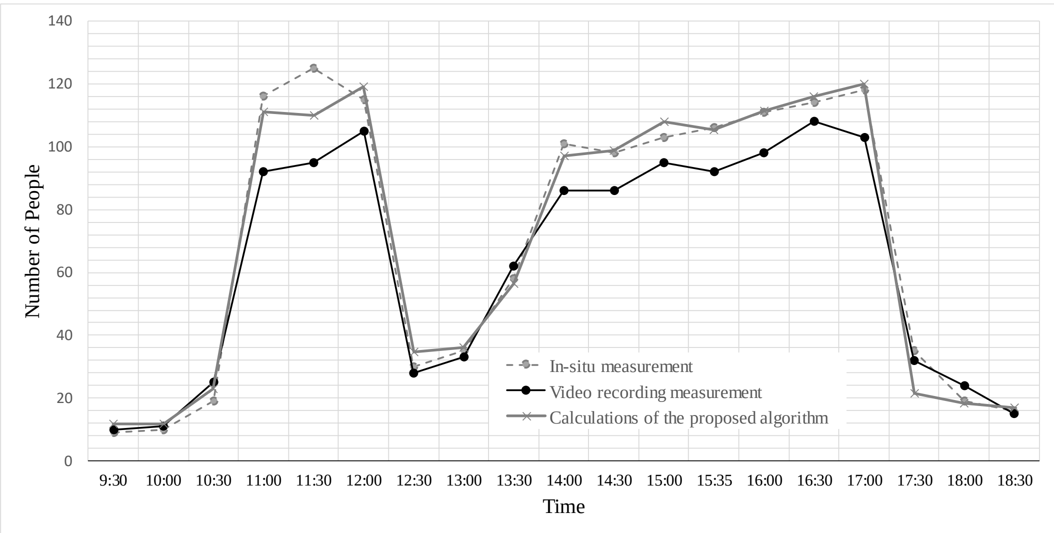


Figure 6: The results of ISM, VRM and the proposed algorithm (24 December, 9:30AM-6: 30 PM)

3.3 Results for Experiment 2

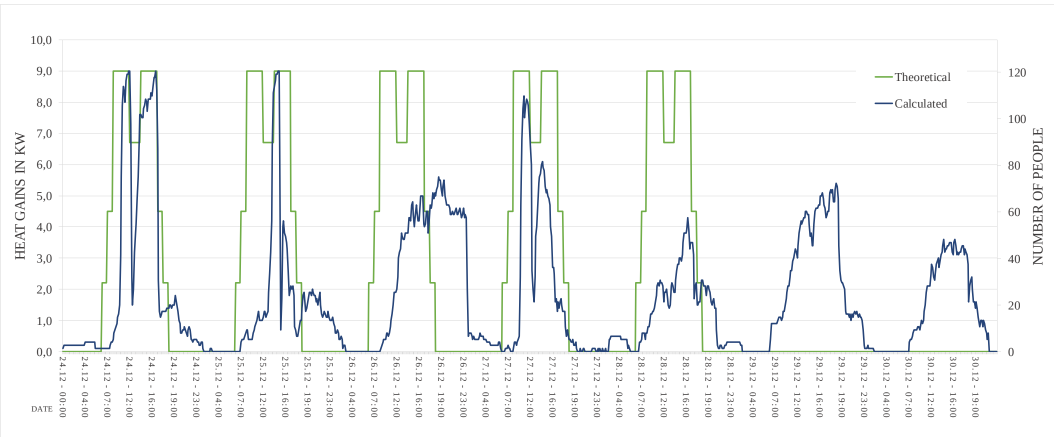
For Experiment 2, building energy simulations were used to quantify the impact of occupancy count on building performance metrics. Two separate energy models were generated for the same classroom. The first directly used the occupancy data calculated using the proposed approach. For the second model, namely the theoretical model, an existing standard dataset for occupant density fraction schedule for classrooms was used by multiplying the hourly schedule values by the maximum number of people expected in the classroom (set to 120). Occupant activity level is set to 144 W/person, which corresponds to standard office work. The following building setup is used for both energy models. Heating setpoint and setback temperatures are 22 C° (5:00AM-6: 00 PM during weekdays) and 18 C° respectively, while natural ventilation is set to activate after 25 C°. The thermal transmittance values of the room surfaces are 3.316, 0.577, 2.84 and 2.6 W/m2-K for the walls, ceiling, floor, and window respectively. Simulations were run for one whole week in mid-spring (15-21 May) and winter (24-30

December), with a frequency of 10 minutes. The resulting performance data is used for benchmarking. The first benchmark metric is total occupant heat gain (kW), which is calculated as the activity level times the number of occupants. The second metric is total heating energy use (kW), calculated only for winter simulations. The last metric is indoor air temperature (C°), calculated only for mid-spring simulations.

It must be noted first that that total number of people are 1803,7 and 2424 by the proposed algorithm and the theoretical dataset respectively. This amounts to a -%25.59 difference between the two datasets. The simulation results indicate that, due to the difference between the total number of people used in the two energy models, the total heat gain, which is independent of seasonal climatic conditions, is subject to decrease with the same amount as occupant count (-%25.59) from theoretical to calculated (Table 2). This places stress on the building energy balance, such that critical building performance criteria change as well. To compensate for the reduced internal load, the heating energy use in winter increases by %12.77 in the energy model that uses data from the proposed approach. In summer, the proposed method estimates the average and maximum indoor air temperature values 0,32 C° and 1,50 C° lower than the theoretical approach respectively. Imprecise performance predictions due to faulty occupancy estimation can give way to uninformed decision-making in buildings. Incorrect estimation of heating loads or summer indoor temperatures can misinform HVAC sizing, or lead to incorrect decision-making for building improvement by over- or under-estimating performance problems.

Table 2. Building performance metrics for benchmarking

	Total Heating Energy Use (kW)	**Total Occupant Heat Gain (kW)**	**Average Indoor Temperature (C°)**
Theoretical occupancy	5216.5	2424.0	26.98
Calculated occupancy	5882.6	1803.7	26.67
Difference	%12.77	-%25.59	-%1.15



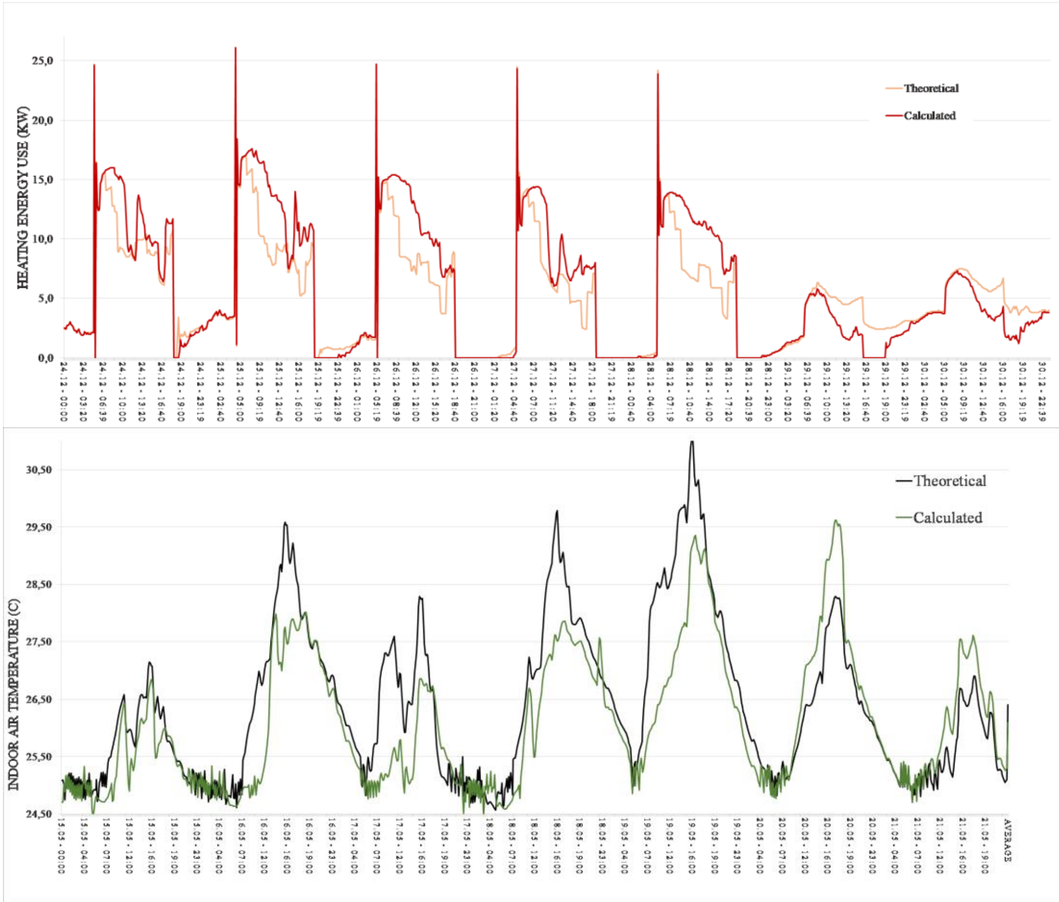


Figure 7. People heat gain, building heating energy use (winter) and indoor air temperature (mid-spring) values

4. Discussion and Conclusion

This paper proposed an approach that counts the people in a room from video content through head detection and tracking. A hybrid method was developed that uses the head detection algorithm for estimating the number of people. The method was evaluated in a classroom environment for a week. Despite the occlusion and image resolution problems due to the high number of people and the size of the room, it is observed that the highest average percentage error was 11%. In the future, we plan to improve the proposed approach by increasing the number of samples of the dataset for increased performance. Moreover, the resulting occupant count was used in the energy simulations of the same room, and the acquired results were benchmarked against an existing standard occupancy schedule. The results show that the difference in the two data sets has a critical influence on building performance metrics of heating energy use and indoor air temperature.

Acknowledgments

The authors would like to acknowledge the support by the TUBITAK – British Council Newton – Katip Celebi Fund, Grant No. 217M519.

References

Agency, I. E. (2018). *EBC Annex 66 Definition and Simulation of Occupant Behavior in Buildings*.

Akkaya, K., Guvenc, I., Aygun, R., Pala, N., & Kadri, A. (2015). *IoT-based Occupancy Monitoring Techniques for Energy-Efficient Smart Buildings*. 58–63.

Amin, I. J., Taylor, A. J., Junejo, F., Al-Habaibeh, A., & Parkin, R. M. (2008). Automated people-counting by using low-resolution infrared and visual cameras. *Measurement: Journal of the International Measurement Confederation*, *41*(6), 589–599. https://doi.org/10.1016/j.measurement.2007.02.010

Andriluka, M. (2008). People-Tracking-by-Detection and People-Detection-by-Tracking. *2008 IEEE Conference on Computer Vision and Pattern Recognition*, 1–8. https://doi.org/10.1109/CVPR.2008.4587583

Benezeth, Y., Laurent, H., Emile, B., & Rosenberger, C. (2011). Towards a sensor for detecting human presence and characterizing activity. *Energy and Buildings*, *43*(2–3), 305–314. https://doi.org/10.1016/j.enbuild.2010.09.014

Day, J., Theodorson, J., & Van Den Wymelenberg, K. (2012). Understanding controls, behaviors, and satisfaction in the daylit perimeter office: A daylight design case study. *Journal of Interior Design*, *37*(1), 17–34. https://doi.org/10.1111/j.1939-1668.2011.01068.x

Duarte, C., Van Den Wymelenberg, K., & Rieger, C. (2013). Revealing occupancy patterns in an office building through the use of occupancy sensor data. *Energy and Buildings*, *67*, 587–595. https://doi.org/10.1016/j.enbuild.2013.08.062

Dziedzic, J., Yan, D., & Novakovic, V. (2017). Occupant migration monitoring in residential buildings with the use of a depth registration camera. *Procedia Engineering*, *205*(1877), 1193–1200. https://doi.org/10.1016/j.proeng.2017.10.352

Galoogahi, H. K., Fagg, A., & Lucey, S. (2017). Learning Background-Aware Correlation Filters for Visual Tracking. *Proceedings of the IEEE International Conference on Computer Vision*, *2017-Octob*er, 1144–1152. https://doi.org/10.1109/ICCV.2017.129

Gilani, S., Brien, W. O., Gilani, S., & Brien, W. O. (2017). *Review of current methods, opportunities, and challenges for in-situ monitoring to support occupant modeling in office spaces occupant modeling in office spaces*. *1493*(July). https://doi.org/10.1080/19401493.2016.1255258

Han, J., & Bhanu, B. (2007). A fusion of color and infrared video for moving human detection. *Pattern Recognition*, *40*(6), 1771–1784. https://doi.org/10.1016/j.patcog.2006.11.010

Henriques, J. F., Caseiro, R., Martins, P., & Batista, J. (2015). High-speed tracking with kernelized correlation filters. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *37*(3), 583–596. https://doi.org/10.1109/TPAMI.2014.2345390

Hoes, P., Hensen, J. L. M., Loomans, M. G. L. C., Vries, B. De, & Bourgeois, D. (2009). *User behavior in whole building simulation*. *41*, 295–302. https://doi.org/10.1016/j.enbuild.2008.09.008

Hong, T., Yan, D., D'Oca, S., & Chen, C. fee. (2017). Ten questions concerning occupant behavior in buildings: The big picture. *Building and Environment*, *114*, 518–530. https://doi.org/10.1016/j.buildenv.2016.12.006

Kelly Seryak, J., & Kissock, K. (2003). Occupancy and behavioral effects on residential energy use. In *American Solar Energy Society*.

Labeodan, T., Zeiler, W., Boxem, G., & Zhao, Y. (2015). Occupancy measurement in commercial office buildings for demand-driven control applications - A survey and detection system evaluation. *Energy and Buildings*, *93*, 303–314. https://doi.org/10.1016/j.enbuild.2015.02.028

Lam, K. P. (2015). International Energy Agency Energy in Buildings & Communities Programme Annex 66: Definition and simulation of occupant behavior in buildings. *In 9th Energy Forum*.

Karpacz, Poland.

Liu, W., Anguelov, D., Erhan, D., Szegedy, C., Reed, S., Fu, C. Y., & Berg, A. C. (2016). SSD: Single shot multi-box detector. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 9905 LNCS*, 21–37. https://doi.org/10.1007/978-3-319-46448-0_2

Lukežič, A., Vojíř, T., Čehovin Zajc, L., Matas, J., & Kristan, M. (2018). Discriminative Correlation Filter Tracker with Channel and Spatial Reliability. *International Journal of Computer Vision*, *126*(7), 671–688. https://doi.org/10.1007/s11263-017-1061-3

Müller, M., Bibi, A., Giancola, S., Alsubaihi, S., & Ghanem, B. (2018). TrackingNet: A Large-Scale Dataset and Benchmark for Object Tracking in the Wild. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *11205 LNCS*, 310–327. https://doi.org/10.1007/978-3-030-01246-5_19

O'Brien, W., Gunay, B., Tahmasebi, F., & Mahdavi, A. (2017). Special issue on the fundamentals of occupant behavior research. *Journal of Building Performance Simulation*, *10*(5–6), 439–443. https://doi.org/10.1080/19401493.2017.1383025

Peng, D., Sun, Z., Chen, Z., Cai, Z., Xie, L., & Jin, L. (2018). *Detecting Heads using Feature Refine Net and Cascaded Multi-scale Architecture*. 2528–2533. https://doi.org/10.1109/ICPR.2018.8545068

Redmon, J., & Farhadi, A. (2017). YOLO9000: Better, faster, stronger. *Proceedings - 30th IEEE Conference on Computer Vision and Pattern Recognition, CVPR 2017*, *2017-Janua*, 6517–6525. https://doi.org/10.1109/CVPR.2017.690

Reinhart C. F., & K., V. (2003). Monitoring manual control of electric lighting and blinds Reinhart, C.F.; Voss, K. NRCC-45701. *Lighting Research and Technology*, *35*(3), 243–260.

Ren, S., He, K., Girshick, R., & Sun, J. (2017). Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *39*(6), 1137–1149. https://doi.org/10.1109/TPAMI.2016.2577031

Sarkar, A., Fairchild, M., Salvaggio, C., Color, M., & Imaging, D. (2008). *Integrated Daylight Harvesting and Occupancy Detection Using Digital Imaging*. *6816*, 1–12.

Schweiker, M., Kingma, B. R. M., & Wagner, A. (2017). Evaluating the performance of thermal sensation prediction with a biophysical model. *Indoor Air*, *27*(5), 1012–1021. https://doi.org/10.1111/ina.12372

Toftum, J. (2010). Central automatic control or distributed occupant control for better indoor environment quality in the future. *Building and Environment*, *45*(1), 23–28. https://doi.org/10.1016/j.buildenv.2009.03.011

Yoshino, H., Hong, T., & Nord, N. (2017). IEA EBC annex 53: Total energy use in buildings—Analysis and evaluation methods. *Energy and Buildings*, *152*(July), 124–136. https://doi.org/10.1016/j.enbuild.2017.07.038

Zivkovic, Z., & Van Der Heijden, F. (2006). Efficient adaptive density estimation per image pixel for the task of background subtraction. *Pattern Recognition Letters*, *27*(7), 773–780. https://doi.org/10.1016/j.patrec.2005.11.005

Effectiveness of a Novel Untethered Augmented Virtuality System for Immersive Industrial Training

Mahmudul Hassan[1]*, Ludovico Carozza[2], Frédéric Bosché[3], Mohamed Abdel-Wahab[4]
[1]SED, Teesside University
[2]FiveAI
[3]School of Engineering, University of Edinburgh
[4]School of Computing, Engineering and Physical Sciences, University of the West of Scotland
* email: m.hassan@tees.ac.uk

Abstract

The application spectrum of Immersive technologies, i.e. Virtual Reality (VR) and Mixed Reality (MR), is expanding but their effectiveness is often constrained by critical factors such as the restricted 6DOF movement of the VR user, limited immersion level and restrained interactions within the VR scene. This paper proposes a novel untethered self-embodiment based Augmented Virtuality (AV) system named Immersive Hybrid Reality (iHR), that aims to address these issues. The iHR system allows VR users to roam around the (scalable) VR workspace, untethered with 6DOF thanks to an external state of the art infrared tracking system. Furthermore, immersiveness is increased by blending spatially the 3D structural information of the near ambience of the VR user (real world), particularly the limbs (i.e. hands and legs) with the VR scene. This AV solution also enables the VR user to interact with real and virtual objects simultaneously. The effectiveness of the proposed iHR system is assessed against typical VR technologies in the context of immersive industrial training (i.e. offshore wind turbine nacelle inspection). A set of attributes are first identified to measure user experience and performance level. These then make up a comparative survey, for which the results exhibit the superior impact of iHR over typical VR systems in the industrial training domain.

Keywords: Hybrid Reality, Self-embodiment, Serious game, VR training performance measures.

1. Introduction

Current immersive technologies such as Virtual Reality (VR) and Mixed Reality (MR) have seen unprecedented popularity in recent times due to the increasing availability of powerful consumer VR hardware. Their application has been considered in various domains e.g. Construction Training [1] and Industrial Education [8]. Yet, they possess few fundamental limitations that bound the potential effectiveness of these technologies, such as: restricted **6 Degree-of-Freedom (DOF)** movement of the VR user [2], limited immersion level and restrained interactions within the VR scene [3]. This is more apparent in instances when VR users have to perform **self-affordance -based** tasks [4].

The realism and effectiveness of the immersive experience are maximized when the users completely suspend their sense of disbelief during the virtual experience [5]. At the same time, preserving the sense of reality, for example by correctly perceiving the user's body and other ambient real objects pertinent to the VR scenario, can make the VR experience more realistic and engaging [6]. Additionally, the immersive experience can be elevated to a substantial degree, especially, in the case where the VR experiences are task-oriented (the VR user himself has to perform a task), if the VR users are permitted to roam around a sizable VR working space untethered [7]. Another dimension in the VR applications can be added if the VR users are able to interact in a continuous and simultaneous manner with both virtual and real objects. This is particularly evident in VR based industrial training applications [8], where ideally the interaction of the user with real tools is very important and should ideally be preserved within the VR experience (possibly alongside virtual interactions). For example, it can be important for manual trade training that the trainee be able to perceive his presence immersed within the working environment, safely experiencing potentially hazardous and distressing situations (e.g. working at heights) and at the same time be able to grasp and manipulate real tools and materials (i.e. harnesses, hammer, etc. In simpler terms, the immersive system should not only provide high-level self-embodiment, but also an effective mechanism to accommodate interaction with both real and virtual objects simultaneously.

This paper proposes a novel untethered self-embodiment -based Augmented Virtuality (AV) system named Immersive Hybrid Reality (iHR), which addresses these issues. The iHR allows VR users to roam around the VR workspace (scalable), untethered with 6DOF thanks to an external state of the art infrared tracking system. The immersiveness is further increased by blending spatially consistently the 3D structural information of the near ambience of the VR user (real world), particularly the limbs (i.e. hands and legs), with the VR scene. This AV solution also provides the VR user with the opportunity to interact with real and virtual objects simultaneously.

We have evaluated the effectiveness of our proposed iHR against the state-of-the-art VR technologies for immersive industrial training. This evaluation was conducted using a comparative survey assessing aspects of performance and user experience. The scarcity of already validated measurement metrics to measure the performance, effectiveness and user experience of immersive systems in an industrial training setting has obliged us to conduct research and propose a specific set of parameters.

The contribution of the paper is thus four folds: **(1)** Free 6-DOF motion within scalable volume: Our proposed system is fully wearable and untethered, which permits the free movement of the VR user within a volume of 5m×5m×3m, that is easily scalable. **(2)** The proposed iHR system uses an ego-centric RGBD camera to capture the visual and structural (i.e. 3D) information surrounding the user. That information is processed and filtered, and relevant objects within the vicinity (the extent of the real space can be controlled) of the user are integrated to the VR content in a spatially-consistent manner to form the AV, or HR, view displayed to the user through the HMDs. These real objects particularly include the user's limbs, which enhances the level of self-embodiment and affordance. In particular, this enables the user to interact with their hands (not avatar) with real objects, while immersed, which is of significant value for industrial training, particularly for manual trades. **(3)** We propose a set of parameters (combining key elements and influencing factors from the most contemporary fields of Virtual Reality (i.e. education, entertainment, edutainment) and also from quintessential industrial training modules) which attempt to measure the training effectiveness, as well as the performance and user experience of VR systems. **(4)** We provide a comprehensive comparative analysis between iHR and contemporary VR technologies by means of paired experiments and associate survey conducted with college trainees.

2. Previous Works

2.1 General Approaches for Enhancing Self-Embodiment

Some of the leading works and relevant immersive setups from the literature are described in this section, with focus on enhancing presence/self-embodiment. The set-up presented in [9], called AR-RIFT, provides a video see-through AR HMD by mounting two monocular cameras on an Oculus Rift headset in correspondence to the two eyes' positions, so that the real world can also be 'seen' through the Oculus Rift. The resulting immersiveness are noticeable, due to the large field of view (FOV) achieved. However, this set-up acquires the real scene and performs the rendering of the virtual content independently on the two camera images without any stereo matching, so that not full, stereoscopy is achieved. Accordingly, real depth information is not available and virtual/real object interaction cannot be fully consistent. A similar hardware set-up is used in [10], where an AV system is employed to investigate height perception. In this work, only hands/arms are extracted from the real scene based on a colour model (separately on the two camera images). As mentioned by the authors, the main limitations of this approach are the low frame rate (14 fps) and most importantly the lack of real depth information, which prevents correct occlusion handling. In [11] the authors propose a novel AV approach that partially blends reality and virtuality, and they study the effect of varying the amount of blending of the two. Like us, preserving the sense of touch on real objects while being immersed in a virtual environment is considered important for user presence awareness when performing a task. According to the author themselves, since the system is not able to perform true stereoscopy, real depth cannot be measured, and the user can just roughly orientate himself within the real environment. The system described in [12] employs a set-up very similar to ours. The user's hands are reconstructed from the RGB-D camera data, and coloured thimbles attached to fingers are tracked to simulate simplified grabbing of virtual objects. However, the user is tethered to a dedicated workstation performing hand reconstruction while head movements are tracked by a 6-DOF optical tracking system. No calibration procedure between the depth camera and the HMD is reported, although it is clearly critical to the correct perception of the real environment within the virtual environment, and accordingly the correct execution of reach and grab tasks of real objects. It is worthwhile to note that they report results on the assessment of the user experience in term of (increased) self-embodiment. This assessment, however, focuses on the manipulation of virtual objects only.

2.2 Mixed Reality for Training

A number of works have described the benefits and limitations of mixed reality for training of procedural tasks in manual trades, broadly in manufacturing [13] and construction [14]. Below we discuss recent works that are particularly relevant to the scope of this paper. The work in [15] aim to assess the effectiveness of AR for conducting real basic assembly tasks, like building LEGO structures, providing error detection (e.g. missing model parts) and virtual guidance during the process. The approach proposed in [16] aims at tracking manual workflow in first-person videos and assessing its correctness by comparison with video examples. In [16] a bare hand (gesture recognition) interface that provides different modalities of guidance depending on the user cognitive stage (perception, attention, memory and execution) is presented. Detection of objects and associated tools is marker-based and allows tracking and augmentation with virtual components, as well as their manipulation for on-site assembly simulation. In construction, mobile AR has seen applications mainly in maintenance assistance [17] and collaborative visualization of construction processes. The study in [18] provides preliminary insights regarding the experience of assembly/disassembly sequences using an immersive set-up similar to ours, to assess the effect of ownership of the user's hands while dragging virtual components. We are not aware of works targeting the assessment of procedural tasks conducted with real tools and materials while experiencing challenging simulated/virtual working conditions. The current work represents an extension of the works in [19] and [20]. In those works, a proof-of-concept of a training system based on a tethered static prototype of the iHR was presented. In the current paper, a novel fully wearable untethered version is presented. Furthermore, a first study is reported on the formal assessment of the effectiveness of the system on immersion and affordance.

2.3 User Experience and Performance Evaluation

User Experience (UX) in Immersive Virtual Environment (IVEs) can be measured by both subjective methods (e.g. questionnaires, interviews etc.) and objective methods (e.g. electroencephalogram, electromyogram, task completion time, level reached) [21]. Currently, questionnaires are considered the most popular method for measuring the UX components, thanks to a number of reliable and valid questionnaires already available. In contrast, the state-of-the-art objective methods available today for quantitative UX assessment are still questionable [21], while remaining costly. In this work, a questionnaire is used solely.

A review of the literature showed a lack of existing questionnaire containing all the components of UX relevant to the context of industrial training, while also addressing performance evaluation. For example, the Simulator Sickness Questionnaire (SSQ) [22] is a popular questionnaire to measure the physical constraints of the user while in the VR world. In contrast, the Immersive Tendencies Questionnaire (ITQ) [23] is applied to measure the level of immersion of the user within the virtual environment. A few questionnaires such as [24] endeavor to explore most of the components of UX in IVE, such as presence, flow, usability, technology adoption, immersion etc. But usually these questionnaires are designed to explore the UX in IVE from a video gaming perspective, thus excluding key independent features that are important to safe and effective training and can be good indicators for

VR based training system evaluation, (e.g.: communication capability of a VR user with others outside the VR space, or safety while immersed in the VR space). When reviewing the literature on conventional industrial trade training [25] and VR based simulation training [26], the following independent UX and Performance attributes are identified that are of relevance to the case of industrial/manual training in an IVE setting:

Physical constraints: Physical constraints are one of the important aspects of any training mechanism. With the increased use of HMD and VR ready backpacks, their long-term use can trigger discomfort and unusual posture related issues [27]. Exposure to the HMD displays for longer periods can also lead to eye strain and hygiene related issues [28]. Moreover, Visually-Induced Motion Sickness (VIMS) is a major impediment to the growth of VR.

Visual Quality: The visual quality of VR HMDs (i.e. resolution, Field of View etc.) is critical to enhance the sense of presence [29], and thus the quality of VR-based training.

Tracking quality and space: To support an immersive and realistic VR experience, the tracking system should be accurate, have low latency with a fast refresh rate, and be robust [30]. Moreover, the size of the trackable space is also critical for VR based industrial training as the VR user often requires performing non-static physical activities that include substantial movements [30].

Safety: Safety is a big concern that the users face in a modern HMD based VR [31], a user wearing an HMD, most likely along with headphones, is functionally blind and deaf in real-world terms. This can lead to physical accidents. Furthermore, this leads to users focusing less on the game/training.

Presence, Energy and Immersion: Presence is defined as the user's 'sense of being there' in the virtual environment. Energy is defined as the 'energy in action, the connection between a person and his/her activities consisting of a behavioral, emotional and cognitive form'. And lastly, Immersion is defined as the 'illusion that the virtual environment technology replaces the user's sensory stimuli through the virtual sensory stimuli'. These are the core attributes of any VR system, determining the effectiveness of the system. From the industrial IVE training perspective, these components are also undoubtedly important. For example, when health and safety training is provided for working at height [32], a proper balance between presence and immersion can produce effective training outcomes.

Communication: During VR-based training, users may need to respond to queries of trainers, and more generally may have to communicate with the trainer, for example by pointing at certain parts of the virtual environment while commenting about them.

Tool Usage: The majority of conventional industrial training processes involve different tools/objects [33] (i.e. Harness etc.). For VR-based training of industrial/manual workers, being able to use real tools and materials (as opposed to virtualized ones) within the IVE could be valuable.

3. The iHR System

Figure 1) provides an overview of the system with its main functional components.

Localisation: We use a scalable *OptiTrack Motive* Tracking system (with Flex13 cameras), operated by a Desktop PC (labelled *Tracking Workstation* at Figure 1). The optical tracking system is calibrated to cover a tracking area of approx. 6m x 5m with a position accuracy of 3.4 mm (mean 3D error). We use this system to track with, a frequency of 120 Hz, the 3D position and orientation of a rigid body made up by a set of seven IR markers mounted rigidly on the HMD (


(a)


(b)

Figure 2. (a): VR HMD with reflective markers and mounted RGB-D camera. (b): Occlusion between real entities (hand) and virtual (turbine equipment) is correctly represented. (a)). The location information provided by the Optitrack Tracking system is then communicated wirelessly from the server *Tracking Workstation*) to the client (*Wearable Computing Unit*). The client then integrates this

information with the IMU data of the VR HMD (Oculus Rift) to deliver precise and latency-free head pose estimations. Further details about our complete localisation approach can be found in [19-20].

Hybrid Reality (Augmented Virtuality): To capture the structural data of the surrounding environment, an RGB-D camera (Softkinetic DS325) is mounted integrally to the HMD (Oculus Rift, see

(a)

(b)

Figure 2. (a): VR HMD with reflective markers and mounted RGB-D camera. (b): Occlusion between real entities (hand) and virtual (turbine equipment) is correctly represented. (a)).

Following noise filtering, the RGB-D data is then processed to segment and reconstruct in real time a smooth representation of the surface (textured 3D mesh) of surrounding real objects (e.g. user hands or tools). Figure 2(b) shows an example of the system capabilities to correctly handle occlusions between real and virtual entities (in both directions) in a wind-turbine maintenance scenario. The generated textured mesh is expressed in the RGBD camera's reference frame and must be transformed into the HMD's reference frame to be correctly perceived by the user within the scene. Accordingly, we developed a calibration process [20] which estimates the rigid transformation between the two reference frames. This calibration ensures that reaching and grasping of real objects is possible without removing the HMD. In our context, this means that tools (e.g. hammer) and real mock-ups of parts of working environments manipulated during training (e.g. hooks for harness anchoring) are correctly aligned within both the field of view and with the 'extending' virtual environment. The data processing framework described above is implemented as a C++ plugin for Unity 5 game engine.

Wearability and motion freedom: The wearable system (*Wearable Computing Unit* in Figure 1, is basically a VR-ready backpack, to which the HMD and the depth camera are connected. The backpack performs all the RGBD data processing and game rendering tasks along wirelessly receiving the 6DOF location data packets from the *Tracking Workstation*. As stated earlier, the location information provided by the Optitrack Tracking system is then communicated wirelessly to the wearable system. This is done using an ad-hoc wireless network. Being the size of the packets of few bytes, this stage does not impact at all on the overall performance (e.g. by introducing latency). This means that the user just carries a 3.6Kg backpack (and headset) that is completely untethered. As a result, the users are able to navigate freely and fully untethered, which is rare in typical VR systems.

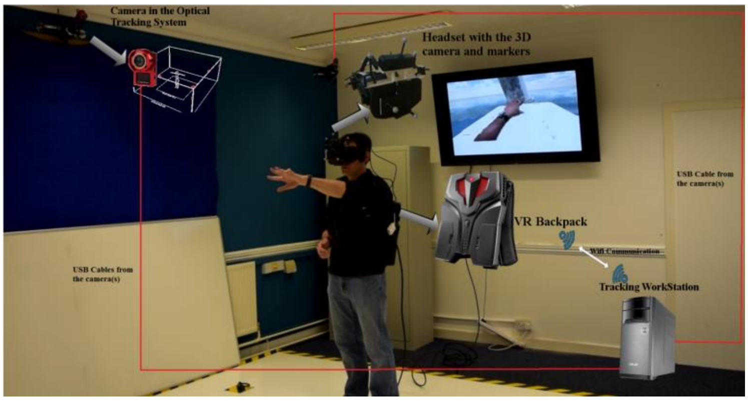


Figure 1: Schematic overview of the iHR system.


(a)


(b)

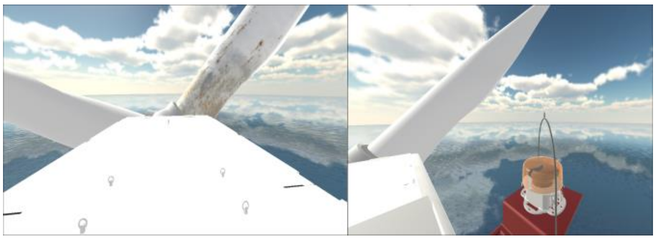
Figure 2. (a): VR HMD with reflective markers and mounted RGB-D camera. (b): Occlusion between real entities (hand) and virtual (turbine equipment) is correctly represented.

4. User Experience and Performance Evaluation

The proposed system is piloted to evaluate its UX and other performance related features in comparison with contemporary immersive VR technology, in the context of an industrial training scenario. The comparison is assessed through a post experience survey.

4.1 Experimental Setup

In order to conduct the survey, an IVE based 'Wind turbine nacelle inspection' game and training session were set. The game consists of a 3D model of an actual offshore wind turbine. The trainees are virtually placed on top of the turbine nacelle, the game automatically generates a random set of typical defects for each training session that the trainees must detect. The defects include: rust on a blade, crack on a blade etc. Figure 3(a) shows examples of the user's view of some of those defects.



(a) (b)

Figure 3. (a): Examples of random defects generated in the turbine nacelle (i.e. Rust on the blade, broken navigation light). (b): The iHR wind turbine maintenance training system

The training session was conducted in a 5m×4m room which was augmented with a 4m×2.5m mock-up model of the top surface of the nacelle equipped with four typical safety anchors (Figure 3(b)). The Optitrack tracking system setup for that room uses 6 "Flex13" cameras mounted on the room walls. A group of 10 participants took part in the experiment. The participants were wind turbine maintenance trainees, who did not have any prior experience of being at the top of a turbine. Each participant was asked to complete the following two tasks involving two distinct activities (1) Being hooked, explore the virtual game environment to find defects, while in iHR mode. (2) Being hooked, explore the virtual game environment to find defects, while in VR mode. The sample size for this study is arguably small, but this was due to the fact that the 10 participants constituted the entire year cohort on that programme.

4.2 Questionnaire

Following the completion of the tasks, the trainees were given a questionnaire to fill in. The questionnaire contains 25 questions that capture the user's opinions regarding their experience of the virtual environment and game in both VR and iHR modes. The questions are inspired by existing questionnaires from the literature, related to VR based training and non-VR training: Simulator sickness questionnaire [22], Presence questionnaire [34], User experience questionnaire [24], Nasa TLX questionnaire [33], and Immersive tendencies questionnaire [23]. All the 25 questions comprising the questionnaire use a 5-point Likert scale. For analysing the statistical significance within the responses, we use two statistical significance tests:

Pearson's Chi-Squared test. For the responses that were categorical/nominal in nature and did not involve any comparison aspects, we have applied the Pearson's Chi-Squared test [34]. In this statistical test, the test statistic is a Chi-Square random variable $\chi^2(p)$, and the Null Hypothesis is rejected if the $\chi^2(p)$ value does not exceed the critical value (α) that depends on the Degree of Freedom (DF) and the probability value of ($P(X \leq x)$) or if the Test Statistic value exceeds the Critical value (obtained from the χ^2 single tailed table).

Wilcoxon signed-rank test. For the responses which are ordinal in nature (i.e. 5- point Likert scale) and are used to compare the iHR system against the VR system, we use the Wilcoxon signed-rank test [35]. The Wilcoxon procedure computes a test statistic W_{STAT} that is compared to an expected value and the null hypothesis is rejected if the value remains lower than $W_{CRITICAL}$ value. There is been a longstanding dispute about the most valid way to analyse Likert data, which are discrete, ordinal, and have a limited range. The basic choice is between a parametric test (i.e. student's t-test) and a nonparametric test (i.e. Wilcoxon signed-rank test). Since Likert scale data typically do not follow the "normal distribution", we use the Wilcoxon signed-rank test (which can be considered as an alternative to the paired student-t test) [35].

4.3 Results - Comparison of iHR and VR

Physical Constraints: Three questions are asked to the participants in relation to physical constraints: One about eye strain; one about motion sickness; and one about the weight of the backpack. The questions regarding the eye strain and motion sickness are comparative in nature (between VR and iHR). The backpack configuration is common in both systems and thus does not yield any comparative response. Table 1 reports the results regarding eye strain and motion sickness. It shows that the participants did not feel any substantial physical constraints related to eye strain in both the VR and iHR as the mean (μ) value is similarly very low in both cases (Note: multiple instances of identical scores for both VR and iHR means that the W_{STAT} cannot be calculated). Similarly, the results show, this time with statistical significance, that the participants did not experience significant motion sickness (though the iHR performed slightly better than VR). Regarding the weight of the backpack, all participants unanimously qualified it as 'not heavy'. The weight is clearly not a concern.

Table 1: Results and analysis of statistical significance for the Physical Constraints questions.

Question	System	μ	σ	W_{STAT}	$W_{CRITICAL}$	Significance
Motion Sickness 1-Nil 5-Extreme	VR iHR	2.3 2	.823 1.24	11	5	NS
Eye Strain 1-Nil 5-Extreme	VR iHR	1.1 1.1	0.31 0.31	N/A	5	N/A

$*\rho = 0.05; *df = 4$ $\quad *df = Degree\ of\ Freedom; *\rho = Deee\ of\ Signifinance; *\mu = mean; *\sigma = Std.Daviation$

$*S = Statistically\ Significant$; $*NS = Not\ Statistaccaly\ Significant$; $*N/A = Not\ Applicable$

Visual Quality: Four questions were asked to the participants in relation to 'Visual Quality'. Three questions evaluate the graphical quality of the iHR system and do not involve any comparison. The remaining question compares the overall graphical quality of the VR and iHR systems. The iHR-related questions are about the quality of rendering of real-world objects captured by the HMD-mounted RGBD camera (i.e. participants' own hand and the harness) inside the VR game and the standard (i.e. size) of the *Field of View (FOV)* of the real-world window inside the virtual world *FOV*. Table 2 shows that the visual quality of the iHR rendering is moderately impressive (μ= 3.77 for the hand, and μ=3.22 for the harness), with statistical significance. This said, shiny objects are challenging to capture and render consistently. Furthermore, due to a threshold range of the depth camera, inconsistencies in rendering real objects can be experienced (e.g. walls of the room could sometimes be seen, although beyond the depth camera range threshold). But, as shown in Table 2, the main challenge remains the *FOV* of the range camera (μ=2.11). While this is a result that we expected, it must nonetheless be noted that this result is not statistically significant.

Table 2: Results and analysis of statistical significance for the iHR Visual Quality questions

Question	μ	$\chi^2(p)$	Critical Value	Test Statistic	Significance
Rendering of Hand 1-Not Realistic 5-Very Realistic	3.77	0.028	9.48	10.88	**S**
Rendering of Harness 1-Not Realistic 5-Very Realistic	3.22	0.026	9.48	11.05	**S**
Size of *FOV* 1-Too small 5-Large Enough	2.11	0.287	9.48	5.10	**NS**

$*\alpha = 0.05; * df = 4$ $* df = Degree\ of\ Freedom; * \alpha = Alpha\ Value; * \mu = mean; * \chi2(p) = ProbabilityValue$ $* S = Statistically\ Significant$; $* NS = Not\ Statistaccaly\ Significant$; $* N/A = Not\ Applicable$

Table 3 summarizes the results regarding the comparison of the overall graphical quality between VR and iHR modes. It shows that the users found the graphical quality of the VR (μ=1.8) system better than that of the iHR (μ=3), a result that is statistically significant. This was expected, because of some of the limitations of the iHR system in acquiring and rendering the real world in a fully consistent way, as discussed earlier.

Table 3: Results and analysis of statistical significance for the comparative Visual Quality question

Question	System	μ	σ	W_{STAT}	$W_{CRITICAL}$	Significance
Overall Graphics 1-Excelent 5-Worse	VR iHR	1.8 3	1.032 0.666	2	5	**S**

Tracking Quality and Space: Five questions investigate the performance in terms of 'tracking quality and space'. Three comparative questions relate to the motion tracking quality in both VR and iHR conditions. The remaining two questions focus on the untethered tracking space. Since both the VR and iHR systems use the same tracking space and both of them are untethered, these questions are not comparative.

Table 4 summarises the results obtained for the motion tracking quality. The responses first unveil that in both VR and iHR modes, the users did not feel any significant latency (μ=1.8 & μ= 2.0 respectively). Then, the participants reported some instances of judder, slightly higher in the case of iHR. One reason might be the higher computational demand that the iHR has compared to the VR. The W_{STAT} value suggests (minor) significance in the results. Finally, the results show that the participants reported good overall tracking quality for both the VR and iHR modes, and these results are statistically significant.

Table 4: Results and analysis of statistical significance for the comparative Tracking Quality questions

Question	System	μ	σ	W_{STAT}	$W_{CRITICAL}$	Significance
Felt Latency 1-Nil 5-Extreme	VR iHR	1.8 2.0	0.63 0.87	N/A	5	**NA**
Felt Judders 1-Nil 5-Extreme	VR iHR	2.3 2.7	0.48 0.67	5	5	**S**
Overall Tracking 1-Worst 5-Great	VR iHR	4.0 3.6	0.61 0.73	3	5	**S**

Regarding the tracking space, the participants were asked if they had felt complete freedom while roaming around the room. Table 5 summaries the responses and shows that a majority of participants felt that there was enough freedom (μ=3.556), which also shows that the participants felt very little constraint in moving. We argue that this could add to the overall impact on presence and immersion in the VR game.

Table 5: Results and analysis of statistical significance for the Space question

Question	μ	$\chi^2(p)$	Critical Value	Test Statistic	Significance
Level of Freedom 1-Restricted 5-Complete Freedom	3.55	0.013	9.48	12.67	**S**

Safety: Three questions assess the level of safety the participants felt in both the VR and iHR systems. Two questions are concerned with 'tripping' and 'hitting nearby objects' while immersed in the VR and iHR systems. The last question asks the participants to rate the overall level of safety they felt when using both systems. Table 6 summarises the results. Since the iHR system lets the users see their surroundings (within a defined range), it is expected that they can control their motion to some extent and thus feel more confident. The statistics confirm this. The participants undoubtedly had greater concerns of tripping and hitting nearby objects in the VR system (μ=2.3) in comparison with the iHR system (μ=3.4). Similar results are obtained for the risk of hitting nearby objects. Regarding the overall safety, the results show μ=2.3 for the VR system and μ =3.2 for the iHR system, which clearly suggests that the users felt safer in the iHR system.

Table 6: Results and analysis of statistical significance for the comparative Safety questions

Question	System	μ	σ	W_{STAT}	$W_{CRITICAL}$	Significance
Fear of Tripping 1-Extreme 5-Nil	VR iHR	2.3 3.4	1.33 0.84	2	5	**S**
Fear of Hitting 1-Extreme 5-Nil	VR iHR	2.8 3.6	1.23 0.96	2	5	**S**
Overall Safety 1-Nil 5-Extreme	VR iHR	2.3 3.2	0.98 1.15	3	5	**S**

Presence, Energy and Immersion: Eight questions were designed to measure and compare the Presence (two questions), Energy (one question) and Immersion (four questions) level of the VR and iHR systems. Among these, seven questions were comparative. In Table 7, the first two rows show the results for the questions related to **Presence**. Firstly, they were asked to what level they felt the urge to secure themselves with the harness while in the game, and secondly, they were asked to rate the overall presence for both VR and iHR systems. The results reveal that the participants felt an enhanced sense of presence when using the iHR system, although the result is not statistically significant. In the **Immersion** section, the questions asked the level of feeling at height and anxiety while looking down from the edge of the turbine nacelle in the game. The answers of the first question show that they felt the height substantially more in iHR than in VR, although opposite results are revealed for the level of anxiety. This may be explained by the fact that, since the participants could see their body in particular legs while walking and looking down the edge, they were more confident in controlling their body movement (and thus surer about their own safety) which subsequently helped to reduce the level of anxiety. Moreover, due to the erroneous/inconsistent reading from the depth camera, the users sometimes could see portions of the ground within the iHR, which may also have contributed in reducing the level of anxiety. In the third question, the participants were asked how fast they felt they lost awareness of the real world and felt immersed in the VR world. According to their answers, we can see the iHR was better at immersing the players in the virtual environment. In the last question, the participants were asked to rate the overall Immersion level of the two systems. As expected from the results above, the iHR proved substantially more immersive than the VR. We note that of all the results in the Immersion section, only the result to the second question (anxiety level) was not statistically significant. For measuring the **Energy** within the game, the participants were asked if they felt any urge to touch/ interact with the virtual objects (which linearly correlates with the level of energy). The result shows that thanks to being able to see their own hands the participants had greater urge to interact (subsequently energy) with the virtual objects in the iHR system (μ=3.7) than in the VR system (μ=2.4).

For the Presence, Energy and Immersion attribute, one last question solely related to the iHR asked the participants if the self-embodiment feature of the iHR improved/ increased the level of presence. As Table 8 shows, the participants agreed that self-embodiment helped increase the presence.

Table 7: Results and analysis of statistical significance for the comparative Presence, Energy and Immersion questions

Question	System	μ	σ	W_{STAT}	$W_{CRITICAL}$	Significance
Presence						
Urge of Securing 1-Nil 5-Extreme	VR iHR	3.1 3.5	0.99 0.52	3	5	**S**
Overall Presence 1-Nil 5-Extreme	VR iHR	3.4 3.9	0.84 0.56	N/A	5	**N/A**
Immersion						
Felt Height 1-Nil 5-Extreme	VR iHR	3.0 3.7	0.47 1.05	4	5	**S**
Anxious of Height 1-Nil 5-Extreme	VR iHR	3.7 3.0	1.42 0.82	11	5	**NS**
Loose Awareness 1-Slow 5-Fast	VR iHR	2.9 3.5	0.87 0.70	5	5	**S**
Overall Immersion 1-Nil 5-Extreme	VR iHR	2.7 3.7	0.67 0.82	3	5	**S**
Energy						
Urge to Touch 1-Nil 5-Extreme	VR iHR	2.4 3.7	0.52 1.16	2	5	**S**

Table 8: Results and analysis of statistical significance for the iHR Presence question

Question	μ	$\chi^2(p)$	Critical Value	Test Statistic	Significance
Level of Presence (1-Increased Hugely 5-Didn't Increase)	1.66	0.026	9.48	11.05	**S**

Communication: Two questions assess the iHR and VR systems as a communication medium. The first question asks to rate (compare) the overall ease of communication by the VR game user with an external person in both VR and iHR conditions. Table 9 summarises the results and shows that the participants strongly endorse that the iHR system provides a better communication medium.

A second question asks to give an opinion on the specific hypothesis that 'being able to point with their own hands made the communication easier in the iHR condition'. Table 10 summarises the results and shows, with statistical significance, that the participants strongly believe that self-embodiment enhances communication.

Table 9: Results and analysis of statistical significance for the comparative Communication question

Question	System	μ	σ	W_{STAT}	$W_{CRITICAL}$	Significance
Communication 1-Easy 5-Difficult	VR iHR	3.2 2.0	0.91 0.94	3	5	**S**

Table 10: Results and analysis of statistical significance for the iHR Communication question

Question	μ	$\chi^2(p)$	Critical Value	Test Statistic	Significance
Self-embodiment and Communication 1-Easy 5-Difficult	.0	0.013	9.48	12.67	**S**

Tool Usage: To measure the value of the iHR system to support the manipulation of actual objects/tools while immersed, the participants were asked whether being able to manipulate real tools/objects while training, like the harness, was helpful for effective training. The results summarised in Table 11 show that the participants agreed (μ=1.9), with statistical significance.

Table 11: Results and analysis of statistical significance for the iHR Tool Usage question

Question	μ	$\chi^2(p)$	Critical Value	Test Statistic	Significance
Level of Presence (1-Increased Hugely 5-Didn't Increase)	1.9	0.023	9.48	11.34	**S**

5. Conclusion and Future Direction

The paper has presented a fully untethered AV system that seamlessly integrates, both visually and structurally, the local real world surrounding the user within the virtual environment. We refer to such new form of MR as Hybrid Reality (HR). The set-up of the system was fully described, and its benefits were compared experimentally with typical VR through a piloting involving college trainees. Experimental results suggest, with some statistical significance, the benefits of the proposed system for IVE -based industrial training, in comparison with typical VR. The self-embodiment and spatially consistent rendering features of the iHR substantially increase the presence and immersion level of the users. Furthermore, the HR functionality enables users to use real objects/tools, which can often be critical for industrial training. The untethered nature of the system enables users to enjoy 6-DOF motion freedom within a scalable space. While this enables more active training, the HR functionality effectively balances the enhanced safety concerns deriving from such freedom. Finally, the iHR showed its value in allowing VR users to communicate effectively with people in the outside world (e.g. trainers).

The piloting also highlighted some limitations of the proposed iHR system. In particular, hardware limitations of the depth camera (i.e. erroneous depth readings, and limited FOV) negatively impacted the visual quality delivered by the iHR. As a result, future studies should focus on increasing hardware capability (i.e. FOV of the depth camera), by at least using new generations of TOF cameras. Furthermore, the HR functionality should be leveraged to design a robust controller-free, hand-based user interface.

References

[1] Hilfert, T., & König, M. (2016). Low-cost virtual reality environment for engineering and construction. *Visualization in Engineering*, *4*(1), 2.

[2] Carozza, L., Bosché, F., & Abdel-Wahab, M. (2014, September). [Poster] Visual-lnertial 6-DOF localization for a wearable immersive VR/AR system. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 257-258). IEEE.

[3] Jin, G., Jiang, K., & Lee, S. (2018). Development of Virtual Reality Games for Motor Rehabilitation. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, *10*(4), 87-94.

[4] Asjad, N. S., Adams, H., Paris, R., & Bodenheimer, B. (2018, August). Perception of height in virtual reality: a study of climbing stairs. In *Proceedings of the 15th ACM Symposium on Applied Perception* (p. 4). ACM.

[5] Apostolopoulos, J. G., Chou, P. A., Culbertson, B., Kalker, T., Trott, M. D., & Wee, S. (2012). The road to immersive communication. *Proceedings of the IEEE*, *100*(4), 974-990.
[6] Ries, B., Interrante, V., Kaeding, M., & Anderson, L. (2008, October). The effect of self-embodiment on distance perception in immersive virtual environments. In *Proceedings of the 2008 ACM symposium on Virtual reality software and technology* (pp. 167-170). ACM.
[7] Gutekunst, M., Geuss, M., Rauhoeft, G., Stefanucci, J., Kloos, U., & Mohler, B. A video self-avatar influences the perception of heights in an augmented reality oculus rift.
[8] Gavish, N., Gutiérrez, T., Webel, S., Rodríguez, J., Peveri, M., Bockholt, U., & Tecchia, F. (2015). Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks. *Interactive Learning Environments*, *23*(6), 778-798.
[9] Steptoe, W., Julier, S., & Steed, A. (2014, September). Presence and discernability in conventional and non-photorealistic immersive augmented reality. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 213-218). IEEE.
[10] cGill, M., Boland, D., Murray-Smith, R., & Brewster, S. (2015, April). A dose of reality: Overcoming usability challenges in vr head-mounted displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 2143-2152). ACM.
[11] Tecchia, F., Avveduto, G., Brondi, R., Carrozzino, M., Bergamasco, M., & Alem, L. (2014, November). I'm in VR!: using your own hands in a fully immersive MR system. In *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology* (pp. 73-76). ACM.
[12] Brown, L. (2018). Holographic Micro-simulations to Enhance Aviation Training with Mixed Reality.
[13] Juang, J. R., Hung, W. H., & Kang, S. C. (2013). SimCrane 3D+: A crane simulator with kinesthetic and stereoscopic vision. *Advanced Engineering Informatics*, *27*(4), 506-518.
[14] Khuong, B. M., Kiyokawa, K., Miller, A., La Viola, J. J., Mashita, T., & Takemura, H. (2014, March). The effectiveness of an AR-based context-aware assembly support system in object assembly. In *2014 IEEE Virtual Reality (VR)* (pp. 57-62). IEEE.
[15] Miller, A., White, B., Charbonneau, E., Kanzler, Z., & LaViola Jr, J. J. (2012). Interactive 3D model acquisition and tracking of building block structures. *IEEE transactions on visualization and computer graphics*, *18*(4), 651-659.
[16] Wang, X., Ong, S. K., & Nee, A. Y. C. (2016). Multi-modal augmented-reality assembly guidance based on bare-hand interface. *Advanced Engineering Informatics*, *30*(3), 406-421.
[17] Rankohi, S., & Waugh, L. (2013). Review and analysis of augmented reality literature for construction industry. *Visualization in Engineering*, *1*(1), 9.
[18] Sportillo, D., Avveduto, G., Tecchia, F., & Carrozzino, M. (2015, August). Training in VR: a preliminary study on learning assembly/disassembly sequences. In *International Conference on Augmented and Virtual Reality* (pp. 332-343). Springer, Cham.
[19] Carozza, L., Bosche, F. N., & Abdel-Wahab, M. S. (2015). An immersive hybrid reality system for construction training. *Proceedings of the 15th CONVR*, *15*, 5-7.
[20] Bosché, F., Abdel-Wahab, M., & Carozza, L. (2015). Towards a mixed reality system for construction trade training. *Journal of Computing in Civil Engineering*, *30*(2), 04015016.
[21] Tcha-Tokey, K., Christmann, O., Loup-Escande, E., & Richir, S. (2016). Proposition and validation of a questionnaire to measure the user experience in immersive virtual environments.
[22] Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, *3*(3), 203-220.
[23] Slater, M. (1999). Measuring presence: A response to the Witmer and Singer presence questionnaire. *Presence*, *8*(5), 560-565.
[24] Tcha-Tokey, K., Loup-Escande, E., Christmann, O., & Richir, S. (2016, March). A questionnaire to measure the user experience in immersive virtual environments. In *Proceedings of the 2016 Virtual Reality International Conference* (p. 19). ACM.
[25] Webster, J., Cabeças, J. M. M., Kuhl, K., Liddle, M., Ellwood, P., Smith, P., ... & Väänänen, V. (2013). Occupational safety and health in the wind energy sector-European Risk Observatory.
[26] Schuemie, M. J., Bruynzeel, M., Drost, L., Brinckman, M., De Haan, G., Emmelkamp, P. M. G., & Van der Mast, C. A. P. G. (2000). Treatment of acrophobia in virtual reality: A pilot study. In *Conference Proceedings Euromedia* (pp. 271-275).

[27] Costello, P. J. (1997). *Health and safety issues associated with virtual reality: a review of current literature* (pp. 1-23). Loughborough, UK: Advisory Group on Computer Graphics.
[28] Bangay, S., & Preston, L. (1998). An investigation into factors influencing immersion in interactive virtual reality environments. *Studies in health technology and informatics*, 43-51.
[29] Baillot, Y., Davis, L., & Rolland, J. (2001). A survey of tracking technology for virtual environments. *Fundamentals of wearable computers and augumented reality*, 67.
[30] Scott Stein. 2016. The dangers of virtual reality. (2016). https://www.cnet.com/news/the-dangers-of-virtual-reality/
[31] Lin, Q., Rieser, J. J., & Bodenheimer, B. (2013, August). Stepping off a ledge in an HMD-based immersive virtual environment. In *Proceedings of the ACM symposium on applied perception* (pp. 107-110). ACM.
[32] Presence, M. S. M. (1999). A Response to the Witmer and Singer Presence Questionnaire Presence. *Teleoperators and Virtual Environments*, *8*, 560-565.
[33] Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology* (Vol. 52, pp. 139-183). North-Holland.
[34] Pearson, K. (1900). X. On the criterion that a given system of deviations from the probable in the case of a correlated system of variables is such that it can be reasonably supposed to have arisen from random sampling. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, *50*(302), 157-175.
[35] Wilcoxon, Frank (Dec 1945). "Individual comparisons by ranking methods" (PDF). *Biometrics Bulletin.* 1 (6): 80–83.

Evaluating immersive and non-immersive VR for spatial understanding in undergraduate construction education

Dragana Nikolic[1] and Ben Windess[1, *]
[1] University of Reading, School of the Built Environment, Whiteknights, Reading RG6 6AG
[*]Email: d.nikolic@reading.ac.uk

Abstract

In this paper we explore a pedagogical value of using immersive virtual reality to teach construction students how to identify and evaluate the spatial characteristics of their design in terms of sizes, layout or structural issues. This study builds on the premise that virtual reality, though generally valuable for design understanding, cannot be treated as a monolithic system when it comes to evaluating its effectiveness for tasks that differ in their objectives. The study extends the work of similar studies that have looked into the claimed benefits of immersion, stereoscopy or interactivity on visual perception and spatial cognition. We compared a desktop-based environment with a fully immersive virtual reality in the form of a wearable VR headset to see if there are any noticeable differences in how students review and evaluate spaces. Thirty-two participants from the first year undergraduate construction program were tasked to walk through a small residential house that incorporated up to 12 intentional design mistakes in terms of the size, layout, position or structural oversight. Initial results suggest that the students using the HMD-type of VR slightly better perform compared to those using the monitor. However, observations of students' interactions with the model while completing the tasks suggest a greater complexity in how the navigation patterns, domain knowledge and technology experience may be affecting the way they perceive the design.

Keywords: virtual reality, immersion, spatial understanding, construction education.

1. Introduction

The design and construction of the built environment is spatial and three-dimensional in nature, but quite often the information about it is represented in an abstracted form such as two-dimensional and symbolic drawings. Students in the early architectural and construction education are challenged to visualize and understand often complex structures and one of the main goals of built environment education is the help students develop such skills. For that purpose, different representational mediums are used – from 2D drawings to more recent computer-generated environments that offer new ways of exploration. Given the importance that a representational medium has in the process of visualization, studies have been performed in search of how such visualization tools could enhance this process. This study builds upon the premise that the medium of representation can have a significant impact on the design process and thus, choosing an appropriate medium is of importance. Previous research has indicated that virtual reality though generally valuable for design understanding, cannot be treated as a monolithic system when it comes to evaluating its effectiveness for tasks that differ in their objectives.

2. Background

In the domain of design and engineering education, we emphasize the importance for the students to develop spatial cognition skills in order to design and evaluate proposed design and construction solutions. Cognition is broadly defined as a complex process that involves interaction of an individual's sensory-motor and neurological systems [1]. Spatial cognition represents an integral part of general cognition and can be defined in basic terms as how one understands space. Spatial cognition involves the processes of perception, storing, recalling, creating, and communicating spatial images [1]. Spatial cognition in the design context has been variously defined as one's understanding of the proportions of a given space [2], way finding or ones' ability to orient in a given space, or the relationship between various spaces [3]. Spatial skills when seen as a component of spatial cognition are generally defined as the ability to understand relationships between three-dimensional objects. In the context of design and construction, spatial skills mainly involve the ability to mentally represent and transform three-dimensional objects, comprehend relationship between objects, and interpret images in the mind. For the students, the ability to visualize space is important for solving spatial tasks. Mental rotation is a commonly used strategy for solving spatial problems in design such as to determine if orthographic views match the isometric view and vice versa. Hence, one of the goals in the education of both architecture and construction students is to enhance spatial cognition and develop the ability to accurately perceive scale and spatial character through design representations.

2.1 The role of representational medium

Studies in psychology provide guidance on visual perception and spatial cognition and their purpose to identify, estimate, or otherwise give meaning to perceived objects and spaces [10]. Being a complex internal information-processing task, the visual perception of representations is greatly affected by the type of those representations [11]. Studies that have explored the role of representations for spatial understanding typically argue that physical scale models or two-dimensional drawings are limiting in accurately representing three dimensional objects. Because of the reduced or abstracted scale and object representation, these forms require the user to exert more effort to visualize objects, spaces and the movement through them [4]. One reason for this is the effort to convert the scale of the model to correspond to own scale. Since the scale of the representational medium does not match that of the observer, the designer is more prone to misinterpret objects and spaces resulting in design errors [4].

Virtual reality or computer generated three-dimensional environment have become increasingly popular in the fields of design and engineering as it offers the possibility to present both small-scale and large-scale spatial information in more interactive, immersive and intuitive manner. When compared to VR, traditional medium is also limiting in that it is static in its nature and cannot represent movement through space and time. Visualization that includes time and motion conveys spatial information more easily, allowing the designer to make better judgments about space and form [9]. Virtual reality provides the quality of experiential learning which is deemed as very useful in assisting the development of spatial skills [5, 6]. The ability to view the model at full scale, such as in fully immersive systems (e.g. HMDs or room-like VR) is argued to support egocentric experience of the spaces and thus, understand better the relative sizes of spaces to own scale. Earlier studies have also argued that virtual reality is a superior learning environment for enhancing spatial skills because of its nature to maintain visual and spatial characteristics of the simulated world (e.g. [7]) whereas Dwyer [8] also emphasized how virtual reality provides an engaging environment, which is stated to have a positive effect on students' motivation and learning. As a learning tool, VR allows students to experience their own creations and manipulate worlds and phenomena that are not always accessible in the real world. This is where VR could enhance the visualization process by augmenting the richness and recall of the information [1].

The main goal of VR systems is to enhance the three dimensional aspect of a designed space, providing an instructional medium that can be very useful in aiding perception of the designed object. Since building information modeling has become central to design and construction practices, these fields seem ideal for taking advantage of what VR has to offer, while considering various stages of the design process and its issues of representation, perception, cognition, and design analysis. As design and construction processes work with visual and spatial data, they are an ideal context for studying the effects of VR technology on spatial cognition.

Still, as we are currently witnessing a proliferation of consumer market VR devices and headsets, the question of their appropriateness and specific benefits for design and construction tasks become even more important. One of the current challenges from the research view is that virtual reality still tends to be largely conceptualized as a singular construct, where the largely proclaimed benefits tend to mask the underlying perceptual complexities of different configurations these technologies carry. The issues of representations and mediums are intrinsically coupled, making it particularly challenging to discern the combinations of specific features and attributes that amplify, rather than hinder and distract from an effective experience or task performance.

2.2. Virtual reality

Research focusing on the benefits of virtual reality for general task performance can be broadly classified into two groups [12] of those that investigate the effects of specific system components, such as field of view [13], head tracking and stereoscopy [14], or navigation [15] on spatial understanding and user performance; and those that attempt to compare immersive systems, such as CAVE with non-immersive systems, such as desktop [16]. The assumption or the assertion that immersive systems are advantageous for spatial understanding [17] stems mostly from the notion that immersive systems provide multiple depth cues that are missing from non-immersive systems. In terms of estimating the size of spaces and objects in VR, studies by Nikolic and Zikic [18, 19] compared various conditions using semi-immersive large screen configurations and monitor-based configurations, revealing a more complex interplay between the VR variables such as field of view, stereoscopy, screen size, levels of detail and realism on spatial understanding. Namely, the perception of object and space sizes can be greatly affected when certain variables work in tandem (e.g. screen size and stereoscopy) leading to significant overestimation of height or depth. In the context of undergraduate architecture education, the findings of these studies suggested the usefulness of having large screens and wide field of view for evaluating spaces in terms of scale and size, as long as detail and realism are kept at low levels.

Research in virtual reality and industry adoption has grown in recent times, paralleling an increase in offer of low cost, scalable solutions and wearable head-mounted displays, such as OculusRift, HTC Vive or even Google cardboard. At the same time, the knowledge of what makes each of these different VR systems and configurations appropriate for a particular use scenario is tied to the specific characteristics of these systems (e.g. single-user vs. multi-user, immersive vs. non-immersive, etc.), and the nature of the tasks and their users [20]. Some of the recent studies exploring the value of such systems for design reviews, constructability or safety training are primarily qualitative in nature, relying on observations, surveys and interviews to understand the applicability of such systems for practical use. Fewer experimental, comparative and user-centered studies reveal a general gap around human factors such as spatial cognition [17] and the value of immersion for data visualization [12].

In the context of engineering and design education, one question we were interested in was whether there was value in introducing immersive VR to support the construction students in understanding the design they are asked to develop as part of their first-year course in information visualization. Namely, for the past couple of years we observed a number of students struggling with understanding the spatial and dimensional relationships between the building components, resulting in common issues such as insufficient or excessive floor heights, stairs problems, floor openings, or structural issues, when designing and representing a small residential house in the forms of 2D drawings, SketchUp and Revit models. Each year we were reconsidering the order of using these three forms of representations to see if there would be an improvement in spatial understanding. Hence, while the typical sequence was to start with 2D and then progress through two 3D models, for the last two years we started by asking students to first model a house in SketchUp before developing the plans and subsequently the same model in Revit. We do not have data to support our anecdotal observations, but our general sense was that even towards the end some common issues with the model would surface.

To explore the potential of immersive VR to support the students in evaluating the spatial characteristics of their designs, we developed a 3D visualization of four variations of the residential house that incorporate various mistakes from past students projects. Our approach was to evaluate the immersive VR effectiveness in the ability for the students to identify those issues compared to viewing the same model on the desktop monitor. The steps and the process are detailed in the following section.

3. Method

To explore how immersive VR and specifically the aspects of scale, stereoscopy and navigation may support undergraduate students in understanding of design spaces, we developed a virtual environment using a small residential house that students in their first year undergraduate education in construction develop as part of their core module. Designed as a between-subjects comparative study, out of 32 participants, 16 students completed the task by navigating the model sitting at a standard lab computer monitor using an x-box controller, while the other half did the same task by wearing Oculus Rift and using the x-box controller. The two systems differed in field of view (immersive vs. non-immersive), stereoscopy (stereo vs. non-stereo) and the general movement (sitting vs. standing and free movement), offering different experience of the environment. We hypothesized that the immersive environment will yield better spatial understanding and student performance compared to the desktop option.

a. Models/stimulus

The visualization environment consisted of four variations of a small residential house adapted from the project brief the first year students are given as part of their course work (Figure 1). The choice of this house was made to balance students' familiarity with it with a potential novelty impact of the immersive technology, and also because the students were still working on the project for their course at the time this study took place. The models were created using Autodesk's Revit 2019 and subsequently exported through Revizto as a navigable virtual environment that could then be loaded into a head-mounted display and integrated with the controllers.

Each of the models contained 12 deliberate design errors taken from the past student submissions as the most commonly found issues. These mistakes have been generally classified into four categories pertaining to scale, layout, dimensional and structural issues, as a way to potentially discern further differences in the ability to identify them (Table 1). During the walkthrough session, the students were asked to identify and indicate out loud whenever they thought there was an issue in the model. Each student was assigned a random house, resulting in four students per house across both conditions.

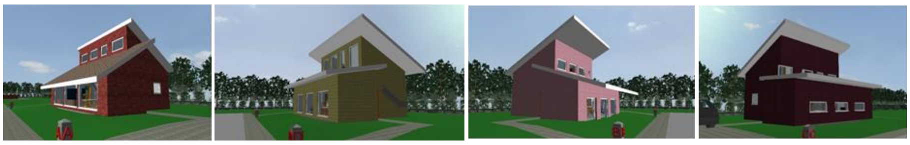


Figure 1: Four residential house models incorporating a set of intentional mistakes

Table 1. Types of intentional design mistake included in the models

Structural	Dimensional	Scale	Layout
Stair floor connection	Windows height	TV	Bathroom elements
Roof overhang	Riser height	Doors (too tall/short)	Missing doors
Roof angle	Stair landing width	Showerhead posit.	Window location
Wall-roof connection	Door thickness	Kitchen cabinets	Furniture location

b. Procedure

The two conditions involved a walk through the model on a 27" computer monitor and a fully immersive OculusRift CV1 where in both settings the students used a standard x-box controller to navigate and exploring a 3D model. This is assumed to be a more intuitive method of navigation for the students compared to the mouse and keyboard option available in the Revizto software. After the participants were greeted and briefed on the nature of the study, they were either seated at the desktop monitor or fitted with the headset and controllers. Before commencing the walkthrough, all the participants were placed first in a small 'training ground' to familiarize themselves with the controls and navigation (Figure 2 left). After they felt comfortable navigating around the training area, they were directed to one of the four passive houses. Given a relatively small size of the house, they were given up to 10 minutes to explore both inside and outside of the building and during that time identify as many building defects as possible (see example in Figure 2 right). As the students were calling out the mistakes as they thought, these were noted down by the researcher. Any items they identified that were not building defects were ignored, but were commented on if appropriate. In addition to asking the students to identify potential mistakes in the model, following the session we also asked them if they felt that they understood better the design in terms of its dimensional and spatial characteristics by completing a seven-item questionnaire. The questionnaire sought to understand any potential differences as a result of their current building technology understanding, familiarity with the technology, and their own perception of their spatial understanding as a result of the experience.

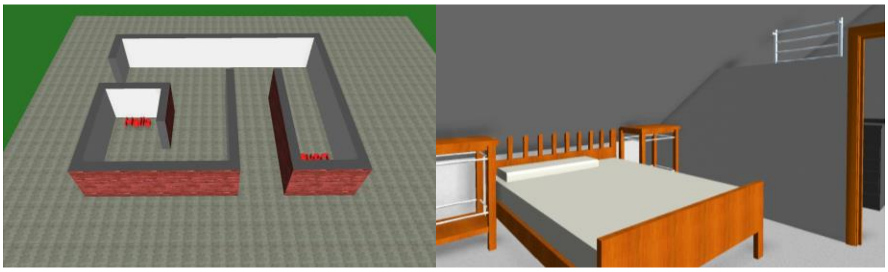


Figure 2: left – training ground; right - low ceiling in one house as an error

4. Findings

Initial results suggest that the students using the HMD-type of VR slightly outperformed those using the monitor. However, observations of students' interactions with the model while completing the tasks suggest a greater complexity in how the navigation patterns, domain knowledge and technology experience may be affecting the way they perceive the design.

A total of 32 participants were divided into 16 participants who used immersive VR and 16 participants who used the monitor which still allowed for reliable trends to be identified [21]. In each of these two groups, four students were assigned to one of each of the four houses. All students were the first year students in the School of the Built Environment enrolled in the 'Information and Communication' module. This was done to maintain relative consistency in students' previous knowledge and experience with the taught material. The co-author who was also their teaching assistant on the module, recruited volunteers so they were not pre-selected based on age, sex, or other their past performance on the module. Of the 32 participants, 12.5% were female and 87.5% were male. Most of the participants were between 18 and 21 years old (97%). Of the VR participants, 38% has never used the headset before.

In terms of the spatial performance and the number of issues detected across the conditions, as mentioned earlier, overall the VR participants slightly outperformed the participants who viewed the model on the monitor (Figure 3). The largest difference was observed for the house labeled B where the participants out of 12 mistakes identified 69% in the VR condition compared to 46% in the monitor condition. Further breakdown per type of spatial issues identified in both conditions reveals the largest variation in scale perception illustrated in two of the houses (A and B) where the number of issues correctly identified in VR condition were far greater (88% for both) than those scores in the monitor condition (38% and 13% respectively) (Figure 5).

Interestingly, the lowest average score in the VR condition (48%) was also the highest average score in the monitor condition. The lowest overall scores were recorded for House A, which may suggest that the types of issues seemed particularly difficult to identify, especially those of dimensional nature (Figure 5).

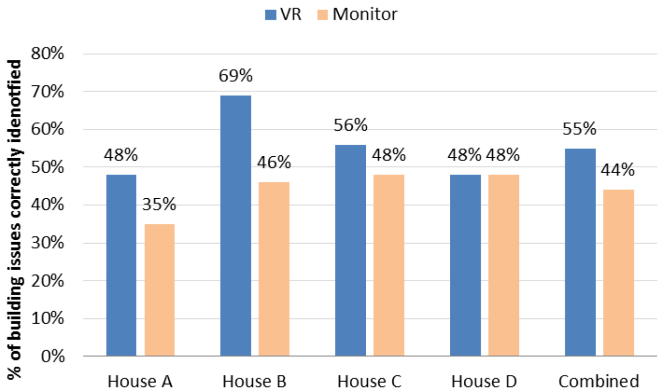


Figure 3: Average number of identified issues viewed in immersive VR and monitor

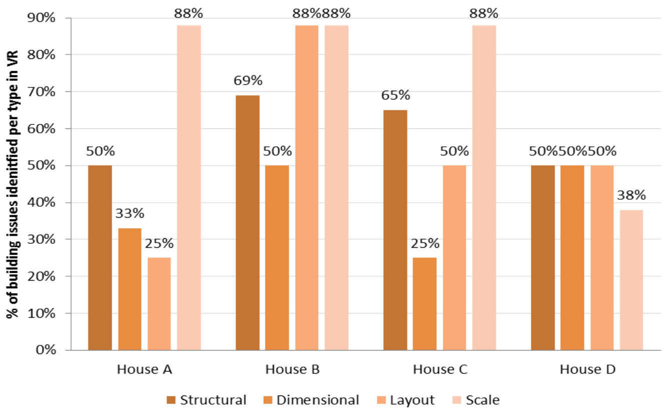


Figure 4: Average number of identified issues per type and per house viewed in VR

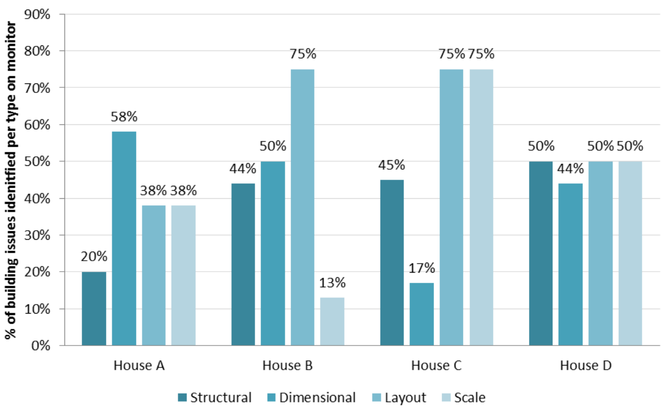


Figure 5: Average number of identified issues per type and per house viewed on the monitor

From both Figure 4 and Figure 5, it can be seen that the scale related issues scored the highest with an average of 59% across both mediums, but with some notable variations in two of the houses (A and B). This suggests to an extent the broader assumption that immersive VR does allow the user to more easily relate the space to own scale compared to non-immersive experience. At the same time, the scores for the structural issues appeared to be lower across both conditions, which could perhaps be in part due to a generally lower level of domain knowledge in construction technologies in the first year. Surprisingly though, the lowest scores were observed for the dimensional types of issues where the average score across both mediums is 42%. Some types of errors may have been more difficult to identify if they were perceived to be open to interpretation (e.g. roof overhang), or were otherwise difficult to easily detect in absence of additional perceptual clues. For example, riser height and the tread depth though obvious to a trained eye, may have been easier for the students to oversee as they could easily jump or fly up the stairs, instead of walk. A perceptual pendant mimicking a physical strain of climbing steep stairs would possibly allow for this design consideration to be more easily spotted.

Though not part of the formal data collection, observations of the participants during the sessions also revealed some interesting interaction instances with the technology, especially with immersive VR. In terms of the movement and exploration, though HMD allows the user to move their head in any direction, a large number of students tended to keep the view at eye level or below. This could have been the factor of the lack of experience with the technology and the reliance on the x-box controller to move the view instead of moving the head. In terms of the user experience with the HMD, one student experienced a slight discomfort after completing the session, which further illustrates the potential of such environments to provoke motion sickness and discomfort, even when the frame rate and the resolution are kept at high levels. Another interesting observation was at times an apparent lack of confidence to call out an issue in the model. There were a number of participants in the VR condition who seemed reluctant to voice their opinion on the design issue, even though they were focusing on it. One of the participants for example, physically crouched down to look through a window that was intentionally positioned too low in one of the rooms on the upper floor, but did not say anything. This again could be attributed to early level domain knowledge, or the lack of confidence in the answer being too obvious.

The last segment of the study asked the students to also share their perception of the usefulness of such approaches to understanding the spatial characteristics of the design with the goal of an improved performance on their project. For this study, we did not look into the course grades to further assess the effects of using VR for longer-term effects on spatial skills. However, the students' responses indicate that the majority of those who participated perceived that the experience was helpful (Figure 6). Those who viewed the models on the monitor seemed to have particularly responded well to the experience compared to those who wore the headset, which could be the result of the familiarity with the setup and fewer perceptual or navigational distractors found in immersive VR.

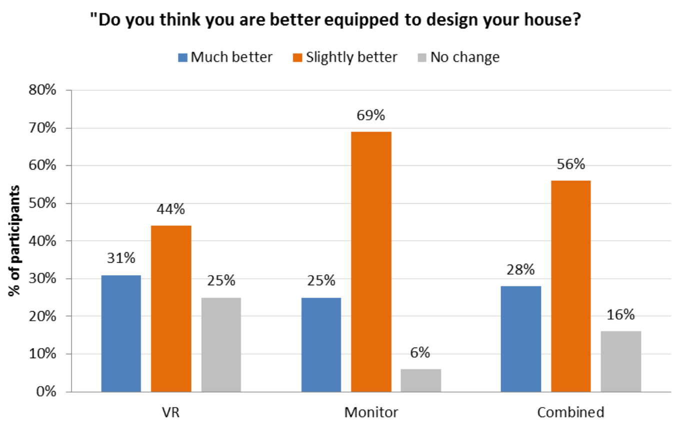


Figure 6: Graph showing the students' responses stating the level of confidence to complete the house project in light of their experience of the technology

5. Conclusions and future work

Overall, the question of how appropriate immersive VR (HMD) is for developing spatial skills in undergraduate education remains sufficiently complex to allow for an easy answer. This study, while indicating some advantages of immersive VR for spatial understanding, also reveals further multi-dimensionality of VR and inherent complexities in how the domain knowledge, novelty effect, content and perceptual differences may influence the spatial understanding and overall performance. Though both conditions overall yielded fairly positive results, questions such as to what extent the ability to interactively walk through the model regardless of the medium benefits understanding spaces, or what are the types of design mistakes that seem to be more difficult to spot in either of the configurations, open the room for additional scrutiny. Human factors such as perceptual differences, gender, level of confidence, affinity towards such technologies, though observed, were not specifically measured or controlled to discern more significant differences in the potential outcomes. Hence, the findings should also be interpreted in light of the study limitations such as the sample size, navigational affordances which allowed teleporting or fly through in addition to walking, and the between-subject study design to claim statistical significance in the findings. Lastly, taking into account the performance on the project after having done the experiment would provide insight into any potential longer term effects of using such technologies for supporting spatial skills.

References

Osberg, K.: Spatial Cognition in the Virtual Environment. Seattle: HIT Lab (1997)

Pinet, C.: Design evaluation based on virtual representation of spaces. In: Proceedings of ACADIA'97 Conference. pp. 111–120 (1997)

Henry, D., Furness, T.: Spatial perception in virtual environments: Evaluating an architectural application. In: Proceedings of IEEE Virtual Reality Annual International Symposium. pp. 33–40 (1993)

Dorta, T., LaLande, P.: The impact of virtual reality on the design process. In: Digital Design Studios: Do Computers Make a Difference? (1998)

Castronovo, F., Oprean, D., Liu, Y., Messner, J.: Application of Immersive Virtual Reality Systems in an Interdisciplinary Design Studio Course. Lean and Computing in Construction Congress - Joint Conference on Computing in Construction. (2017)

Whyte, J.: Industrial applications of virtual reality in architecture and construction. ITcon Vol. 8. 43–50 (2003)

Regian, J.W.: Virtual Reality for Training: Evaluating Transfer. In: Seidel, R.J. and Chatelier, P.R. (eds.) Virtual Reality, Training's Future? Perspectives on Virtual Reality and Related Emerging Technologies. pp. 31–40. Springer US, Boston, MA (1997)

Dwyer, D.: Apple Classrooms of Tomorrow: What We've Learned. Educational Leadership. 51, 4–10 (1994)

Kalisperis, L.N., Otto, G., Muramoto, K., Gundrum, J.S., Masters, R., Orland, B.: Virtual reality/space visualization in design education: the VR-desktop initiative. In: Proceedings of eCAADe2002, design e-ducation: Connecting the Real and the Virtual. pp. 64–71. , Warsaw, Poland (2002)

Palmer, S.E.: Visual Perception of Objects. In: Handbook of Psychology. pp. 177–211. American Cancer Society (2003)

Rice, A.: Exploring the Impact of Emerging Landscape Visualization Tools on Spatial Perception and Design Education. In: Buhmann, E. and Ervin, S. (eds.) Trends in Landscape Modeling. pp. 173–182. Heidelberg: Wichmann (2003)

Schuchardt, P., Bowman, D.A.: The Benefits of Immersion for Spatial Understanding of Complex Underground Cave Systems. In: Proceedings of the 2007 ACM Symposium on Virtual Reality Software and Technology. pp. 121–124. ACM, New York, NY, USA (2007)

Arthur, K.W.: Effects of field of view on performance with head-mounted displays, (2000)

Ragan, E.D., Kopper, R., Schuchardt, P., Bowman, D.A.: Studying the Effects of Stereo, Head Tracking, and Field of Regard on a Small-Scale Spatial Judgment Task. IEEE Transactions on Visualization and Computer Graphics. 19, 886–896 (2013). doi:10.1109/TVCG.2012.163

Balakrishnan, B.: Evaluating Impact of Navigability Affordances and Narrative Transportation on Spatial Presence, (2008)

Swindells, C., Po, B.A., Hajshirmohammadi, I., Corrie, B., Dill, J.C., Fisher, B.D., Booth, K.S.: Comparing CAVE, wall, and desktop displays for navigation and wayfinding in complex 3D models. In: Proceedings Computer Graphics International, 2004. pp. 420–427 (2004)

Paes, D., Arantes, E., Irizarry, J.: Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems. Automation in Construction. 84, 292–303 (2017). doi:10.1016/j.autcon.2017.09.016

Nikolic, D.: Evaluating relative impact of virtual reality components detail and realism on spatial comprehension and presence, (2007)

Zikic, N.: Evaluating Relative Impact of VR Components Screen size, Stereoscopy and Field of View on Spatial Comprehension and Presence in Architecture, (2007)

Whyte, J., Nikolić, D.: Virtual Reality and the Built Environment. Routledge, Milton Park, Abingdon, Oxon ; New York, NY (2018)

Calderon, C.P., van Schaik, P., Hobbs, B.: Is VR an effective communication medium for building design. In: Proceedings of the Virtual Reality International Conference, Laval, France. pp. 46–55 (2000)

An Analytical Review of Tools and Methods for Energy Performance Simulation in Building Design

Ramy Mahmoud*, John M. Kamara, Neil Burford,
[1]School of Architecture, Planning & Landscape, Newcastle University, Newcastle upon Tyne, UK
* email: r.mahmoud2@newcastle.ac.uk

Abstract

With increasing restrictions on energy demands in buildings, Building Energy Performance Simulation (BEPS) tools have been rapidly evolving since their first appearance in the early 1960s. Attempts to merge BEPS with the building design process have faced a number of challenges related to tool technicalities, user-friendliness, and data availability and handling. Thus, a number of practice-based tools have been developed, targeting different types of audience and decision making stages. Also, within academic research, a number of approaches have been adapted from other fields; such as computing and statistical research methods, aimed at assisting early design stage decision making. This study is part of a wider PhD research on the use of BEPS tools in informing architectural decisions in the early design stages. The study covers twofold objective of the larger research through establishing the state of the art in energy modelling tools, to define a categorization and identify recent and emerging trends in their development and application in practice. After performing an investigation into the currently available tools in practice and research, an extensive critical review of the published research in the field of building energy simulation was performed to capture the emerging trends in BEPS between 2008 and 2019. The review resulted in a categorization of 64 tools. It also concluded that emerging trends in the development of BEPS are showing increasing concern for aiding early design decision making. This is evident in the increasing number of tools targeting architects, and those aimed at usage at the early design stage. Also, a variety of tool-formats such as plug-ins have emerged for a higher level of engagement with the design process. Moreover, 66 publications adopting one or more emerging trending energy simulation methods were critically reviewed and listed. Results show a number of trending methods such as sensitivity and uncertainty analysis aiming at overcoming early design decision uncertainties. Also, the cloud-simulation method was found to enable instant simulation results, and artificial intelligence related methods such as genetic algorithms and artificial neural networks were found to assist the optimization and energy prediction process with higher accuracy.

Keywords: Building energy performance, simulation, tools, categorization, trends

1. Introduction

The Architecture, Engineering, and Construction (AEC) industry is undergoing increasingly stringent restrictions regarding energy consumption rates in buildings. The involvement of Building Energy Performance Simulation (BEPS) is increasingly being encouraged at the earlier design stages, as it is here where decisions with the largest impact on the building energy performance are taken (IEA, 2008). BEPS could be described as replicating an aspect of the energy performance of a building through a virtual computational model (De Wilde, 2018). Energy simulation is based on processing a number of thermal parameters, while mimicking building-element heat transfer, in order to calculate the expected energy consumption within a given time interval (Attia, 2012).

The first signs of computer-based BEPS are believed to have appeared in the USA in the early 1960s for designing underground shelters (Kusuda, 1999). Since then, a number of BEPS tools have been developed, targeting services engineers, for calculating technical requirements related to HVAC systems. The aim then was to specify suitable mechanical systems with minimal or no impact on fundamental architectural design decisions, as fuel then was considered inexpensive and the environmental impacts were not yet seriously being considered (Bachman, 2003). With the oil crisis in the 1970s, limitations to energy usage have been increasing. Tools then started to be used for validating architectural decisions at late stages in the design process. By the late 1980s, with the realization of the importance of earlier design decisions, BEPS's evolved to assist decisions taken at different design stages (Augenbroe, 1992). Some of the developed tools targeted architects considering them key decision makers in the early stages (Attia et al., 2009). The concept was that running simulations is more economical than the consequent operational energy costs of the building as a result of poor design (Hensen, 2008). By the end of the 1990s, there were a number of attempts at merging BEPS within the architectural design process such as 'Rijnland Office' and 'ECN Building' in the Netherlands (De Wilde et al., 1999). However, BEPS' integration was found to be significantly more complicated when compared to the smoothness of merging CAAD in the industry (Punjabi and Miranda, 2005). BEPS tools were originally designed to be used by engineers as verification tools at late stages when there is enough data available for use in energy models and simulations. In contrast, earlier design stages are more driven by architects' decisions which by necessity are freer of performance constraints and give rise to increased design and building performance uncertainties. At early stages, designers need user-friendly tools that are capable of providing quick feedback to cope with fast design iterations (Attia, 2012). By the start of the 21st Century, novel trends regarding BEPS tool development and application within practice and research emerged to encompass the nuanced requirements of different audiences at different stages. Novel methods such as cloud-simulation and plug-in options started to emerge to assist the design decision making processes. Notwithstanding, there remain significant barriers to their further adoption, but recent developments in tool capabilities and methods point towards new opportunities for the adoption and greater uptake of simulation tools at different stages in the design process.

Earlier studies were found to compare a number of BEPS software tools according to specific criteria. Based on a field survey, Attia et al. (2009) introduced a comparison between the user-friendliness of 10 simulation tools from architects' point of view, where IES-VE was perceived to be the most user-friendly. Also, it found that only 35 tools from the Building Energy Simulation Tools (BEST) directory were including architects as targeted users. In their comparison, Crawley et al. (2008) have focused on the technical capabilities of 20 BPS tools. The study did not include the usability, target groups nor timing in their comparison. Hopfe et al. (2005) compared 6 randomly selected tools that were meant to be used at the early design stage. The described studies conducted a comparison between limited numbers of tools, while including all building simulation types, without a special focus on the energy aspects. Our research strictly focusses on energy modelling and simulation tools in relation to architectural decision making, while investigating a broader range of tools and studies.

Following the research methodology, findings will be presented within two sections. The first discusses the criteria of the formulated categorization of 64 BEPS tools found to be related to energy analysis in relation to architectural design. The second part discusses the findings of 66 studies which were filtered through a process to extract the novel BEPS trends and methods emerging in the last 10 years.

2. Methodology

The authors have conducted two main areas of research focus. The first investigates currently available energy modelling tools used in the building design process. While the second involves conducting a systematic review of research databases in the period between 2008 and 2019 to extract emerging trends, conceptual approaches and prototype tools used in building energy modelling and simulation.

The primary investigated tool-directory was the BEST directory, formerly owned by the US Department of Energy (BEST, 2019). The directory has been chosen as a reliable international tool-reference according to previous studies (Hopfe *et al.*, 2005; Attia *et al.*, 2013; Yigit and Ozorhon, 2018). The directory includes 198 tools specialized in a number of simulation-related tasks. As the current research is mainly concerned with energy simulation tools that are impacting the architectural design decisions, a filtration criterion was applied; tools which are not related to energy analysis such as those specialised in; lighting performance; acoustics; and airflow, have been excluded. Part of the energy analysis tools related to; post-construction auditing; and billing calculations have been excluded as well as they are not used during the design process. As a final filtering step, tools designed for HVAC, duct and pipe sizing were also excluded as they are not directly related to architectural decisions. The BEST directory does not include all available tools, hence, a part of the systematic review was dedicated to investigating BEPS tools developed in academia. As this study is a part of a wider PhD researching the UK practice, tools used to comply with the energy conservation regulations in the UK were added, these are SBEM and SAP-related tools. The selected tools were then analysed based on the information provided by software developers, in addition to reviewing independent research on the tools.

The second mode of the investigation was undertaken to uncover related research studies into energy performance and building energy simulation methods using variations of a number of keywords related to: Building, Design, Energy, Performance, Simulation/Modelling; Software/Tool*/method*; and their synonyms. The search was mainly performed through the two databases Scopus and Web of Science.

Table 1 : Journal and conference BEPS-related publications

#	Journal	Results
1	Energy and Buildings	132
3	Sustainability	39
4	Applied Energy	35
6	Building And Environment	35
7	Automation In Construction	24
8	Journal Of BPS	25
9	Renewable & Sustainable Energy Rev.	21
10	Building Simulation	20
11	Journal Of Building Engineering	17
12	Energies	15
13	Energy	11
	Total	374

#	Conference	Results
1	Energy Procedia	96
2	IBPSA	90
3	ASHRAE Transactions	69
4	Procedia Engineering	32
5	Building Simulation Applications	29
6	Simulation Series	17
7	PLEA	13
	Total	346

After analysing the preliminary results, the emerging methods and trends were classified and the search terms were refined for subsequent review based on the following terms; Sensitivity analysis; Uncertainty analysis; Parametric analysis; Optimisation; Genetic algorithms; Artificial neural networks; and Cloud-Simulation.

Table 1 summarizes the numbers of investigated publications.

3. Results

The BEST directory includes a total of 198 BPS software tools. Among these, 55 tools claimed they include architects in their user groups. When this is compared with the findings of Attia and De Herde (2011), tools targeting architects have increased from 35 tools in 2010 to 55 in 2019. This supports the suggestion that there is a trend towards encouraging architects to use such tools for early decision making, (Wilde and Voorden, 2004; Attia *et al.*, 2012; Hensen and Lamberts, 2012). After applying the filtering criteria discussed in the Methodology, 42 tools (21%) from the BEST directory were found to criteria. An additional 12 practice-based tools were extracted from the reviewed publications; 9 tools were found to be developed for experimental academic studies (**Error! Reference source not found.**). The main finding regarding the total listed BEPS tools is that nearly the half (54%) are considering architects within their user groups (Figure 1), and 44% of the tools are developed to assist decision making at early phases of the design process (Figure 2).

Regarding the results of the second research mode, the initial publication review using the primary search-keywords provided 1,654 publications. Once filtered, a total of 720 studies were found to be related to the topic (

Table 1). These studies were then further filtered in relation to the earlier mentioned fields, where 66 publications have been analytically reviewed (Table 3 and Table 4).

4. Categorization of BEPS Tools

One aim of the study is to develop a categorization of the available BEPS tools having a direct impact on architectural decisions. The section will aim to categorize a wide range of tools with a focus on early stage. This shall include; user groups; design stage; tool format; and cloud-simulation (**Error! Reference source not found.**).

4.1. User groups

Two approaches could be commonly described regarding the use of BEPS tools in the design stage. The first where architects rely on in-house or outsourced expertise (usually from an engineering background) to undertake the energy analysis, then use the results to inform design decisions (Shelia J. Hayter, 2001). Another approach is for the architects to run the BEPS tools themselves providing real-time feedback through an iterative design process (Attia et al., 2009; Weytjens and Verbeeck, 2010). Engineers and architects are usually seen to be two distinctive user groups, where each has their own educational backgrounds, capabilities, and requirements while using BEPS tools (Alsaadani, 2013).

For engineers to execute energy simulation tasks, they require a clear set of data which should be pre-defined to a certain extent in a developed design and fabric specification, and they tend to deal with pure empirical input and output data in the form of numbers and schedules. On the other hand, architects tend to rely on intuition and rules of thumb, where their early application of BEPS is usually associated with a lack of defined data and specifications leading to high levels of uncertainty (Alsaadani, 2013). They also tend to rely on visual methods rather than empirical forms. Hence, tools for architects are expected to be more user-friendly and with simple Graphical User Interfaces (GUI) (Attia et al., 2009).

The investigated tools could be categorized into three groups; the first is highly technical and directed to engineers such as BSim (around 38% of the tools). This percentage would increase to around 80% when including HVAC design tools (not included in this study). Another group included tools targeting architects, where only 4 tools were found, such as Sefaira. An intermediate group contained tools targeting both user groups such as DesignBuilder (56%). This distribution is illustrated in Figure 1.

4.2. Design stage

Early design decisions are usually described to be the most critical in the building procurement process, and hence, earlier engagement of BEPS is commonly encouraged (MacLeamy, 2004; IEA, 2008). However, it is proclaimed that the majority of the BEPS tools are mainly developed for late verification purposes (Attia *et al.*, 2009; Hensen and Lamberts, 2012). Results show that 46% of the tools are aimed at conceptual design stage. This supports the idea that there is a movement towards developing more tools for early stages. The reaming 54% are developed for design verification purposes (Figure 2).

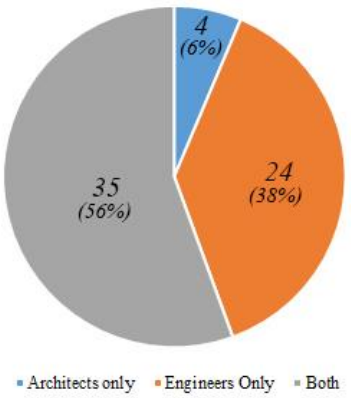


Figure 1: No. tools targeting user groups

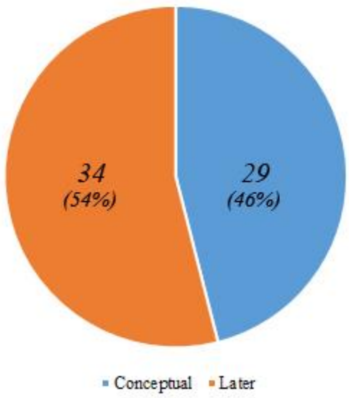


Figure 2: No. tools targeting design stages

Table 2: BEPS tools list

Type	#	Tool	User: Architects	User: Engineers	Des. Stage: Conceptual	Des. Stage: Later	Dependency: Stand-alone	Dependency: Plug-in	Dependency: 3rd Party GUI	Simulation Engine	Cloud Simulation	Parametric Analysis	Reference
Practice-based	1	AET	✓	✓		✓	✓			Own			BEST (2019) BEST Directory | Building Energy Software Tools. Available at: https://www.buildingenergysoftwaretools.com/
	2	Autodesk Insight	✓	✓	✓			✓	✓	Energy+	✓		
	3	BEAVER		✓		✓	✓			Own			
	4	Beopt	✓	✓	✓				✓	Energy+	✓		BEopt (2019) Building Energy Optimization Tool. Available at: https://beopt.nrel.gov/home
	5	Be10	✓	✓		✓				Own			BE10 (2019). Available at: http://www.viegandmaagoe.dk/
	6	BSim		✓		✓	✓			Own			BEST (2019) BEST Directory | Building Energy Software Tools. Available at: https://www.buildingenergysoftwaretools.com/
	7	BuildSimHub	✓	✓	✓		✓			Own	✓	✓	
	8	CAN-QUEST		✓		✓	✓		✓	DOE-2			
	9	CBECC-Com	✓	✓		✓			✓	Energy+			
	10	COMFEN	✓	✓	✓				✓	Energy+			
	11	COMFIE	✓	✓	✓		✓			Own			
	12	cove.tool	✓	✓	✓		✓			Own	✓		
	13	CYPETHERM Suite		✓		✓			✓	Energy+			
	14	DRQAT		✓		✓			✓	Energy+			BerkeleyLab (2019) Demand Response Quick Assessment Tool. Available at: https://drrc.lbl.gov/tools/
	15	DesignBuilder	✓	✓	✓			✓	✓	Energy+	✓	✓	BEST (2019) BEST Directory | Building Energy Software Tools. Available at: https://www.buildingenergysoftwaretools.com/
	16	DOE-2		✓		✓	✓			Own			DOE2 (2018) QUick Energy Simulation Tool. Available at: http://www.doe2.com/equest/
	17	EcoDesigner Star	✓	✓	✓			✓		Own			BEST (2019) BEST Directory | Building Energy Software Tools. Available at: https://www.buildingenergysoftwaretools.com/
	18	EFEN	✓	✓	✓				✓	Energy+			
	19	EnerCAD	✓	✓	✓		✓			Own			
	20	EnergyPlus		✓		✓	✓	✓		Own	✓		
	21	Energy Cost Calc.	✓	✓		✓	✓			Own			
	22	EnergyElephant	✓	✓		✓	✓			Own			
	23	Energy-10	✓	✓	✓		✓			Own			Attia, S. and De Herde, A. (2011), Early design simulation tools for net zero energy buildings: a comparison of ten tools, 12th IBPSA.
	24	ENERWIN Pro		✓		✓	✓			Own			BEST (2019) BEST Directory | Building Energy Software Tools. Available at: https://www.buildingenergysoftwaretools.com/
	25	eQUEST		✓		✓			✓	DOE-2		✓	DOE2 (2018) QUick Energy Simulation Tool. Available at: http://www.doe2.com/equest/
	26	ESBO		✓	✓		✓			Own			BEST (2019) BEST Directory | Building Energy Software Tools. Available at: https://www.buildingenergysoftwaretools.com/
	27	ESP-r		✓		✓	✓			Own			
	28	FineGREEN	✓	✓		✓			✓	Energy+			
	29	gEnergy	✓	✓	✓				✓	Energy+	✓		
	30	Green Building Studio	✓	✓	✓		✓	✓		DOE-2	✓		
	31	HAP		✓		✓	✓			Own			
	32	Honeybee	✓	✓	✓			✓	✓	Energy+		✓	
	33	IDA		✓		✓	✓			Own			
	34	IES VE	✓	✓	✓		✓	✓		Own			
	35	Ladybug	✓	✓	✓			✓		Energy+		✓	
	36	NovaEquer		✓		✓	✓			Own			
	37	N++		✓	✓				✓	Energy+	✓		EnergyModels (2013) N++ v2014 (E+ v8.1). Available at: http://energy-models.com/forum/n-v2014-e-v81-commercial-version-release
	38	OpenStudio		✓		✓		✓	✓	Energy+	✓		BEST (2019) BEST Directory | Building Energy Software Tools. Available at: https://www.buildingenergysoftwaretools.com/
	39	Parametric Analysis Too	✓	✓	✓				✓	Energy+		✓	OpenStudio (2019) Available at: http://nrel.github.io/OpenStudio-user-documentation/reference/parametric_analysis_tool_2/
	40	PHPP	✓	✓	✓		✓	✓		Own			PHI (2015) Passive House Planning Package (PHPP). Available at: https://passivehouse.com/04_phpp/04_phpp.htm
	41	Pleiades	✓	✓	✓				✓	Comfie		✓	BEST (2019) BEST Directory | Building Energy Software Tools. Available at: https://www.buildingenergysoftwaretools.com/
	42	Primero Comfort		✓		✓			✓	Energy+			
	43	SAP Tools: EES Design SAP	✓	✓		✓	✓			Own			BRE (2018) Approved software for SAP 2012. Available at: https://www.bre.co.uk/filelibrary/SAP/2012/SAP2012_9-92_software_2018-06-05.pdf
	44	SAP Tools: iQ-Energy SAP											
	45	SAP Tools: FSAP 2012											
	46	SAP Tools: JPA Designer											
	47	SAP Tools: SAPPER											
	48	SBEM	✓	✓		✓	✓			Own			BRE (2013) SBEM: Simplified Building Energy Model. Available at: https://www.bre.co.uk/page.jsp?id=706
	49	Sefaira	✓		✓			✓	✓	Energy+	✓	✓	BEST (2019) BEST Directory | Building Energy Software Tools. Available at: https://www.buildingenergysoftwaretools.com/
	50	SimulationX		✓		✓	✓			Own			
	51	Tas Engineering	✓	✓	✓		✓			Own			
	52	TRACE 700		✓		✓	✓			Own			
	53	TRNSYS		✓		✓	✓			Own			
	54	jess	✓	✓		✓			✓	Energy+	✓		EnSim (2019) JESS Online. Available at: http://cms.ensims.com/index.php/jess-online
	55	jePlus		✓		✓			✓	Energy+			BEST (2019) BEST Directory | Building Energy Software Tools. Available at: https://www.buildingenergysoftwaretools.com/
Research-based	1	BCVTB		✓		✓			✓	Energy+			Pang, X., Bhattacharya, P., O'Neill (2011), Real-time building energy simulation using energyplus and the building controls virtual test bed. 12th IBPSA.
	2	Building Des. Adviso	✓		✓				✓	DOE-2			Papamichael, K., LaPorta, J. and Chauvet, H. (1997) 'Building Design Advisor: automated integration of multiple simulation tools', Automation in Construction, 6(4), pp. 341-352.
	3	HENK		✓	✓		✓			Own			Itard, L. (2003), Henk, a software tool for the integrated design of buildings and installations in the early design stage. 8th IBPSA.
	4	HTB2		✓	✓			✓		Own			Jones, P., Lannon, S. and Li, X. (2013) Intensive building energy simulation at early design stage.
	5	MIT Design Advisor	✓		✓		✓			Own			Urban, B. and Glicksman, L. (2006) 'The MIT Design Advisor–A fast, simple tool for energy efficient building design', Proceedings of SimBuild, 2(1).
	6	NZEBO	✓		✓				✓	Energy+			Attia, S., Gratia, E., De Herde, A. and Hensen, J. (2013) 'Tool for design decision making: Zero energy residential buildings in hot humid climate', 13th IBPSA, pp. 3720-3727.
	7	Riuska		✓		✓			✓	DOE-2			Jokela, M., Keinänen, A., Lahtela, H., Lassila, K. and Oy, I.O.G. (1997) Building Simulation.
	8	SST2009	✓	✓		✓	✓			Own			Crobu, E., Lannon, S., Rhodes, M. and Zapata, G. (2013), Simple simulation sensitivity tool, 13th IBPSA.
	9	Virtual Design Studio	✓	✓	✓		✓			Own			Pelken, P.M., Zhang, J., Chen, Y., Rice, D.J., Meng, Z., Semahegn, S., Gu, L., Henderson, H., Feng, W. and Ling, F. (2013) Building Simulation. Springer.

4.3. Tool format

BEPS tools could be used as; stand-alone platform; plug-in within an authoring design tool; third-party GUI (Figure 3). Stand-alone software (55% of the tools) are mainly operated through own developed interface and rely on built-in calculation/simulation engines, such as EnergyPlus and DOE-2. Other tool-types are used as plug-ins within other CAAD authoring tools such as Sketchup and Revit. While some of the plug-in tools are limited to being in this format, some are originally stand-alone or 3rd party GUIs that have developed a plug-in to facilitate their integration within the design process. 12 tools (19%) were found to support a plug-in option. A number of research studies have suggested that one of the main reasons architects avoid using BEPS tools is poor user interfaces and data handling complexity. Hence, a number of tools were specifically developed as 3rd party GUIs combining one or more of the simulation tools; examples of those are N++ and eQuest. Also, there are some tools which were developed for academic research purposes such as ZEBO. These count for 40% of the tools.

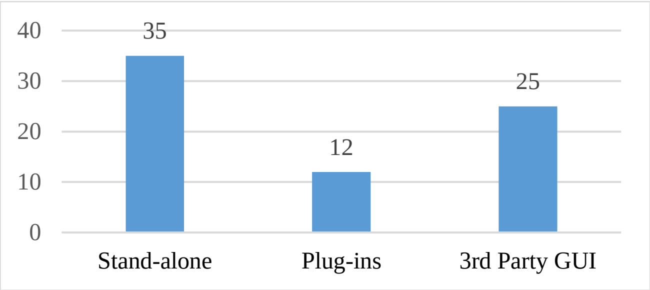


Figure 3: Number of tools with different formats

4.4. Cloud-simulation

The early design stage is usually associated with high iteration frequency when different decisions are assessed and compared. Reliance on conventional simulation hardware which requires long simulation times may then not be a practical solution. Cloud-simulation has allowed for offering real-time feedback as the simulation process is conducted on the cloud rather than on conventional systems, and hence, reducing the processing requirements of computers running the simulation. Cloud-simulation is increasingly being seen as the future by tool-developers, especially those focusing on the early design stages (Attia *et al.*, 2013; Macumber *et al.*, 2014). To underline this, Samuelson et al. (2016) conducted an intensive test running around 90,000 simulations via cloud services within reasonable timing and cost. 18% of the tools such as Green Building Studio were found to adopt cloud-simulation (**Error! Reference source not found.**).

5. Emerging Trends in Building Energy Simulation Application

Review of the emerging trends in development and application of BEPS showed that 66 publications were adopting one or more of these trending methods to assist early design decisions; uncertainty analysis; sensitivity analysis; parametric analysis; genetic algorithms; and artificial neural networks.

5.1. Uncertainty Analysis and Sensitivity Analysis

Early design decisions are usually accompanied by a high level of uncertainty due to lack of data, and a large amount of unknown variables, resulting in uncertainties essential for making confident decisions. This has led to a developing trend in using statistical methods based on Uncertainty Analysis (UA). The role of UA is attempting to quantify the number of uncertainties of different variables to make the decision-making process more reliable through quantifying the simulation results based on the uncertainties of the input variables (Hopfe et al., 2007). UA would aid in giving reliability to the simulation results, which assists the design process when comparing different outcomes.

Table 3 : UA, SA, and PA related studies

#	Study	UA	SA	PA	Source
1	(Anton and TĂnase, 2016)			✓	Anton, I. and TĂnase, D. (2016) 'Informed Geometries: Parametric Modelling and Energy Analysis in Early Stages of Design', Energy Procedia, 85, pp. 9-16.
2	(Banihashemi *et al.*, 2017)			✓	Banihashemi, S., Ding, G. and Wang, J. (2017) 'Developing a hybrid model of prediction and classification algorithms for building energy consumption', Energy Procedia, 110, pp. 371-376.
3	(Berger & Mendes, 2017)		✓		Berger, J. and Mendes, N. (2017) 'An innovative method for the design of high energy performance building envelopes', Applied Energy, 190, pp. 266-277.
4	(Bre *et al.*, 2016)		✓		Bre, F., Silva, A.S., Ghisi, E. and Fachinotti, V.D. (2016) 'Residential building design optimisation using sensitivity analysis and genetic algorithm', Energy and Buildings, 133, pp. 853-866Bre, F., Silva, A.S., Ghisi, E. and Fachinotti, V.D. (2016) 'Residential building design optimisation using sensitivity analysis and genetic algorithm', Energy and Buildings, 133, pp. 853-866.
5	(Burhenne *et al.*, 2013)	✓			Burhenne, S., Tsvetkova, O., Jacob, D., Henze, G.P. and Wagner, A. (2013) 'Uncertainty quantification for combined building performance and cost-benefit analyses', Building and Environment, 62, pp. 143-154.
6	(Delgarm *et al.*, 2018)		✓		Delgarm, N., Sajadi, B., Azarbad, K. and Delgarm, S. (2018) 'Sensitivity analysis of building energy performance: A simulation-based approach using OFAT and variance-based sensitivity analysis methods', Journal of Building Engineering, 15, pp. 181-193.
7	(Elbeltagi *et al.*, 2017)			✓	Elbeltagi, E., Wefki, H., Abdrabou, S., Dawood, M. and Ramzy, A. (2017) 'Visualized strategy for predicting buildings energy consumption during early design stage using parametric analysis', Journal of Building Engineering, 13, pp. 127-136.
8	(Faggianelli *et al.*, 2017)	✓			Faggianelli, G.A., Mora, L. and Merheb, R. (2017) 'Uncertainty quantification for Energy Savings Performance Contracting: Application to an office building', Energy and Buildings, 152, pp. 61-72.
9	(Figueiredo *et al.*, 2016a)		✓		Figueiredo, A., Figueira, J., Vicente, R. and Maio, R. (2016a) 'Thermal comfort and energy performance: Sensitivity analysis to apply the Passive House concept to the Portuguese climate', Building and Environment, 103, pp. 276-288.
10	(Figueiredo *et al.*, 2016b)		✓		Figueiredo, A., Kämpf, J. and Vicente, R. (2016b) 'Passive house optimization for Portugal: Overheating evaluation and energy performance', Energy and Buildings, 118, pp. 181-196.
11	(García *et al.*, 2016)			✓	García Kerdan, I., Raslan, R., Ruyssevelt, P. and Morillón Gálvez, D. (2016) 'An exergoeconomic-based parametric study to examine the effects of active and passive energy retrofit strategies for buildings', Energy and Buildings, 133, pp. 155-171.
12	(Hopfe & Hensen, 2011)	✓			Hopfe, C.J. and Hensen, J.L.M. (2011) 'Uncertainty analysis in building performance simulation for design support', Energy and Buildings, 43(10), pp. 2798-2805.
13	(Jaboyedoff *et al.*, 2015)			✓	Jaboyedoff, P., Cusack, K., Bhanware, P., Ganesan, K., Chetia, S. and Maithel, S. (2015) 14th International Conference of IBPSA - Building Simulation 2015, BS 2015, Conference Proceedings.
14	(Jaffal *et al.*, 2009)			✓	Jaffal, I., Inard, C. and Ghiaus, C. (2009) 'Fast method to predict building heating demand based on the design of experiments', Energy and Buildings, 41(6), pp. 669-677.
15	(Lara *et al.*, 2017)			✓	Lara, R.A., Naboni, E., Pernigotto, G., Cappelletti, F., Zhang, Y., Barzon, F., Gasparella, A. and Romagnoni, P. (2017) Energy Procedia.
16	(Li *et al.*, 2013)			✓	Li, Z., Lin, B., Lv, S. and Peng, B. (2013) Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association.
17	(Manfren *et al.*, 2013)	✓			Manfren, M., Aste, N. and Moshksar, R. (2013) 'Calibration and uncertainty analysis for computer models - A meta-model based approach for integrated building energy simulation', Applied Energy, 103, pp. 627-641.
18	(Naboni *et al.*, 2013)			✓	Naboni, E., Zhang, Y., Maccarini, A., Hirsch, E. and Lezzi, D. (2013) Building Simulation Applications.
19	(Nikolaidou *et al.*, 2017)	✓			Nikolaidou, E., Wright, J.A. and Hopfe, C.J. (2017) 'Robust building scheme design optimization for uncertain performance prediction'.
20	(Olofsson *et al.*, 2009)			✓	Olofsson, T., Andersson, S. and Sjögren, J.U. (2009) 'Building energy parameter investigations based on multivariate analysis', Energy and Buildings, 41(1), pp. 71-80.
21	(O'Brien *et al.*, 2011)			✓	O'Brien, W.T., Athienitis, A.K. and Kesik, T. (2011) 'Parametric analysis to support the integrated design and performance modeling of net zero energy houses', ASHRAE Transactions, 117, pp. 945-960.
22	(Østergård *et al.*, 2017a)		✓		Østergård, T., Jensen, R.L. and Maagaard, S.E. (2017a) 'Early Building Design: Informed decision-making by exploring multidimensional design space using sensitivity analysis', Energy and Buildings, 142, pp. 8-22.
23	(Østergård *et al.*, 2017b)		✓		Østergård, T., Jensen, R.L. and Maagaard, S.E. (2017b) 'Interactive Building Design Space Exploration Using Regionalized Sensitivity Analysis', IBPSA.
24	(Pratt and Bosworth, 2011)		✓		B Pratt, K. and E Bosworth, D. (2011) 'A method for the design and analysis of parametric building energy models', Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association.
25	(Pudleiner & Colton, 2015)		✓		Pudleiner, D. and Colton, J. (2015) 'Using sensitivity analysis to improve the efficiency of a Net-Zero Energy vaccine warehouse design', Building and Environment, 87, pp. 302-314.
26	(Samuelson *et al.*, 2016)			✓	Samuelson, H., Claussnitzer, S., Goyal, A., Chen, Y. and Romo-Castillo, A. (2016) 'Parametric energy simulation in early design: High-rise residential buildings in urban contexts', Building and Environment, 101, pp. 19-31.
27	(Schlueter et al, 2009)			✓	Schlueter, A. and Thesseling, F. (2009) 'Building information model based energy/exergy performance assessment in early design stages', Automation in construction, 18(2), pp. 153-163.
28	(Schwartz *et al.*, 2017)		✓		Schwartz, Y., Raslan, R., Korolija, I. and Mumovic, D. (2017) 15th International Building Performance Simulation Association Conference, San Francisco, CA, Aug.
29	(Sesana *et al.*, 2011)		✓		Sesana, M.M., Salvalai, G. and Esposito, F. (2011) PLEA 2011 - Architecture and Sustainable Development, Conference Proceedings of the 27th International Conference on Passive and Low Energy Architecture.
30	(Shiel *et al.*, 2018)			✓	Shiel, P., Tarantino, S. and Fischer, M. (2018) 'Parametric analysis of design stage building energy performance simulation models', Energy and Buildings, 172, pp. 78-93.
31	(Singh *et al.*, 2016)	✓	✓		Singh, R., Lazarus, I.J. and Kishore, V.V.N. (2016) 'Uncertainty and sensitivity analyses of energy and visual performances of office building with external venetian blind shading in hot-dry climate', Applied Energy, 184, pp. 155-170.
32	(Spitz *et al.*, 2012)	✓	✓		Spitz, C., Mora, L., Wurtz, E. and Jay, A. (2012) 'Practical application of uncertainty analysis and sensitivity analysis on an experimental house', Energy and Buildings, 55, pp. 459-470.
33	(Suh *et al.*, 2011)			✓	Suh, W.J., Park, C.S. and Kim, D.W. (2011) Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association.
34	(Sun *et al.*, 2015)	✓			Sun, Y., Huang, P. and Huang, G. (2015) 'A multi-criteria system design optimization for net zero energy buildings under uncertainties', Energy and Buildings, 97, pp. 196-204.
35	(Wang & Zhao, 2018)		✓		Wang, Z. and Zhao, J. (2018) 'Optimization of Passive Envelop Energy Efficient Measures for Office Buildings in Different Climate Regions of China Based on Modified Sensitivity Analysis', Sustainability, 10(4), p. 907.
36	(Xu *et al.*, 2017)			✓	Xu, W., Lam, K. and Karaguzel, O. (2017) 15th International IBPSA Conference.
37	(Xu *et al.*, 2018)			✓	Xu, X., Feng, G., Chi, D., Liu, M. and Dou, B. (2018) 'Optimization of performance parameter design and energy use prediction for nearly zero energy buildings', Energies, 11(12).
38	(Yan *et al.*, 2017)	✓		✓	Yan, B., Li, X., Shi, W., Zhang, X. and Malkawi, A. (2017) 'Forecasting Building Energy Demand under Uncertainty Using Gaussian Process Regression: Feature Selection, Baseline Prediction, Parametric Analysis and a Web-based Tool', IBPSA.
39	(Yang *et al.*, 2016)		✓		Yang, S., Tian, W., Cubi, E., Meng, Q., Liu, Y. and Wei, L. (2016) 'Comparison of Sensitivity Analysis Methods in Building Energy Assessment', Procedia Engineering, 146, pp. 174-181.

9 studies of the 66 were found to adopt the UA (Table 3). Another common trend in research is Sensitivity Analysis (SA). SA is applied to comprehend relationships between building parameters. The basic concept is that the building's performance could be enhanced when adjusting the values of the different parameters in relation to each other (Nguyen and Reiter, 2015). SA could be described as a measure of the effect of a certain input on the resulting output in relation to building performance (Saltelli et al., 2004). Hemsath and Bandhosseini (2015) advocate that applying SA at the early design stage would lead to better identification of the parameters with the highest impact on the building performance, and hence assists in reaching better decisions. 16 studies adopted SA (Table 3).

5.2. Parametric Analysis

Another trending method is parametric analysis (PA). PA tests the effects of changes on either one or more building parameters in relation to other parameters related to building efficiency using coordinated formulas (Suyoto et al., 2015). PA is usually performed via visual programming methods, and commonly used in conjunction with UA and SA where one of the main applications is in the field of building energy performance optimisation (Anderson and Tang, 2011). PA is evident in 8 of the 64 listed design tools as an extra feature (**Error! Reference source not found.**). And was used in 21 of the listed studies in Table 3.

5.3. Building Optimisation

Building optimisation (BO) is not a field, but recent novel and emerging methods are being developed to assist early design applications. BO is based on running a number of computational algorithms in order to reach optimal parameter-combinations for the building design (Machairas *et al.*, 2014; Saeed, 2017). BO methods are usually used in energy performance-based design approaches. Despite increasing research in BO, applications remain scarce in practice (Citherlet, 2001). There is believed to be a number of challenges that hinder wider uptake, namely; the process is time-consuming; requires high computational powers; and a high level of expertise.

5.4. Artificial intelligence

The applications of artificial intelligence (AI) in the field of energy prediction and optimisation theory is gaining increasing trust regarding calibrating the optimum parameter permutations in an automated manner (Engelbrecht, 2007). Examples of AI methods are Genetic Algorithms (GA) and Artificial Neural Networks (ANN) which are based on mimicking biological systems by applying a number of algorithms in order to perform different tasks. GA is mainly based on the concept of evolving genetics. It is processed through producing a number of generations with specific parameters. Each generation is simulated and tested in relation to a pre-defined efficiency margin. Optimised parameters are then kept while other parameters are enhanced in a following generation. The process continues until a near-optimal solution is reached (Sha et al., 2019). 24 of the 66 studies adopted GA (Table 4).

ANN imitates the functions of neural networks through simulating arithmetic computational models (Saeed, 2017). To predict the energy performance through a machine learning process, the ANN model consists of a number of nodes where each simulates an equation. The nodes are connected through a network to allow for non-linear calculations. The machine learning process exposes the model to a range of historical simulation results based on a number of input parameters, where on each round, the model is informed that a certain input is expected to provide a certain output (Nguyen et al., 2014). The process is repeated until the nodes have formulated suitable equations that would produce similar results to those produced by other simulation software. Another way is to teach the model real-world input parameters from existing buildings, together with the actual consumption. This assists in reducing the performance gap between simulated and actual readings (Machairas et al., 2014). Although the machine learning process demands very large amount of data and time, the resulting models give faster results compared to conventional simulation. 12 studies in the list were found to use ANN (Table 4).

Among the 64 tools, only EnergyElephant and cove.tool were found to be AI supported (**Error! Reference source not found.**).

Table 4: GA and ANN related studies

#	Study	GA	ANN	Source
1	(Ascione *et al.*, 2016)	✓		Ascione, F., De Masi, R.F., de Rossi, F., Ruggiero, S. and Vanoli, G.P. (2016) 'Optimization of building envelope design for nZEBs in Mediterranean climate: Performance analysis of residential case study', Applied Energy, 183, pp. 938-957.
2	(Ascione *et al.*, 2017)		✓	Ascione, F., Bianco, N., De Stasio, C., Mauro, G.M. and Vanoli, G.P. (2017) 'Artificial neural networks to predict energy performance and retrofit scenarios for any member of a building category: A novel approach', Energy, 118, pp. 999-1017.
3	(Azari *et al.*, 2016)	✓	✓	Azari, R., Garshasbi, S., Amini, P., Rashed-Ali, H. and Mohammadi, Y. (2016) 'Multi-objective optimization of building envelope design for life cycle environmental performance', Energy and Buildings, 126, pp. 524-534.
4	(Banihashemi *et al.*, 2017)		✓	Banihashemi, S., Ding, G. and Wang, J. (2017) 'Developing a hybrid model of prediction and classification algorithms for building energy consumption', Energy Procedia, 110, pp. 371-376.
5	(Bogar *et al.*, 2013)	✓		Bogar, D., Rapone, G., Mahdavi, A. and Saro, O. (2013) Building Simulation Applications.
6	(Bre and Fachinotti, 2017)	✓		Bre, F. and Fachinotti, V.D. (2017) 'A computational multi-objective optimization method to improve energy efficiency and thermal comfort in dwellings', Energy and Buildings, 154, pp. 283-294.
7	(Bre *et al.*, 2016)	✓		Bre, F., Silva, A.S., Ghisi, E. and Fachinotti, V.D. (2016) 'Residential building design optimisation using sensitivity analysis and genetic algorithm', Energy and Buildings, 133, pp. 853-866
8	(Calcerano et al, 2016)	✓		Calcerano, F. and Martinelli, L. (2016) 'Numerical optimisation through dynamic simulation of the position of trees around a stand-alone building to reduce cooling energy consumption', Energy and Buildings, 112, pp. 234-243.
9	(Carlucci *et al.*, 2015)	✓		Carlucci, S., Cattarin, G., Causone, F. and Pagliano, L. (2015) 'Multi-objective optimization of a nearly zero-energy building based on thermal and visual discomfort minimization using a non-dominated sorting genetic algorithm (NSGA-II)', Energy and Buildings, 104, pp. 378-394.
10	(Chen *et al.*, 2018)	✓		Chen, X., Yang, H. and Zhang, W. (2018) 'Simulation-based approach to optimize passively designed buildings: A case study on a typical architectural form in hot and humid climates', Renewable and Sustainable Energy Reviews, 82, pp. 1712-1725.
11	(Dan and Phuc, 2018)		✓	Dan, T.X. and Phuc, P.N.K. (2018) Proceedings 2018 4th International Conference on Green Technology and Sustainable Development, GTSD 2018.
12	(Delgarm *et al.*, 2016b)	✓		Delgarm, N., Sajadi, B., Delgarm, S. and Kowsary, F. (2016) 'A novel approach for the simulation-based optimization of the buildings energy consumption using NSGA-II: Case study in Iran', Energy and Buildings, 127, pp. 552-560.
13	(Dong *et al.*, 2017)		✓	Dong, Q., Xing, K. and Zhang, H. (2017) 'Artificial neural network for assessment of energy consumption and cost for cross laminated timber office building in severe cold regions', Sustainability, 10(1), p. 84.
14	(Fang and Cho, 2017)	✓		Fang, Y. and Cho, S. (2017) 'Building Geometry Optimization with Integrated Daylighting and Energy Simulation', IBPSA.
15	(Ferrara et al., 2018)	✓		Ferrara, M., Sirombo, E. and Fabrizio, E. (2018) 'Automated optimization for the integrated design process: the energy, thermal and visual comfort nexus', Energy and Buildings, 168, pp. 413-427.
16	(Geyer and Schlüter, 2014)	✓		Geyer, P. and Schlüter, A. (2014) 'Automated metamodel generation for Design Space Exploration and decision-making - A novel method supporting performance-oriented building design and retrofitting', Applied Energy, 119, pp. 537-556.
17	(Gossard *et al.*, 2013)	✓	✓	Gossard, D., Lartigue, B. and Thellier, F. (2013) 'Multi-objective optimization of a building envelope for thermal performance using genetic algorithms and artificial neural network', Energy and Buildings, 67, pp. 253-260.
18	(Harkouss *et al.*, 2018)	✓		Harkouss, F., Fardoun, F. and Biwole, P.H. (2018) 'Multi-objective optimization methodology for net zero energy buildings', Journal of Building Engineering, 16, pp. 57-71.
19	(Kumar *et al.*, 2018)		✓	Kumar, S., Pal, S.K. and Singh, R.P. (2018) 'A novel method based on extreme learning machine to predict heating and cooling load through design and structural attributes', Energy and Buildings, 176, pp. 275-286.
20	(Lara *et al.*, 2017)	✓		Lara, R.A., Naboni, E., Pernigotto, G., Cappelletti, F., Zhang, Y., Barzon, F., Gasparella, A. and Romagnoni, P. (2017) Energy Procedia.
21	(Li *et al.*, 2018)	✓		Li, Z., Chen, H., Lin, B. and Zhu, Y. (2018) 'Fast bidirectional building performance optimization at the early design stage', Building Simulation, 11(4), pp. 647-661.
22	(Melo *et al.*, 2017)		✓	Melo, A.P., Lamberts, R., Cóstola, D. and Hensen, J.L. (2017) 'Development of a method to predict building energy consumption through an artificial neural network approach', IBPSA.
23	(Ngo, 2019)		✓	Ngo, N.T. (2019) 'Early predicting cooling loads for energy-efficient design in office buildings by machine learning', Energy and Buildings, 182, pp. 264-273.
24	(Polson *et al.*, 2017)	✓		Polson, D., Zacharis, E., Lawrie, O. and Vagiou, D. (2017) 'Multi-Objective Optimisation In Early Stage Design. Case Study: Northampton University Creative Hub Building', IBPSA.
25	(Powers, 2017)	✓		Powers, A. (2017) 'A Modified Genetic Optimization Algorithm Using Ancestor Path Extrapolation', IBPSA.
26	(Santos *et al.*, 2017)	✓		Santos, L., Schleicher, S. and Caldas, L. (2017) 'Automation of CAD models to BEM models for performance based goal-oriented design methods', Building and Environment, 112, pp. 144-158.
27	(Shi, 2011)	✓		Shi, X. (2011) 'Design optimization of insulation usage and space conditioning load using energy simulation and genetic algorithm', Energy, 36(3), pp. 1659-1667.
28	(Tuhus & Krarti, 2010)	✓		Tuhus-Dubrow, D. and Krarti, M. (2010) 'Genetic-algorithm based approach to optimize building envelope design for residential buildings', Building and Environment, 45(7), pp. 1574-1581.
29	(Xu *et al.*, 2018)		✓	Xu, X., Feng, G., Chi, D., Liu, M. and Dou, B. (2018) 'Optimization of performance parameter design and energy use prediction for nearly zero energy buildings', Energies, 11(12).
30	(Yi and Malkawi, 2009)	✓		Yi, Y.K. and Malkawi, A.M. (2009) 'Optimizing building form for energy performance based on hierarchical geometry relation', Automation in Construction, 18(6), pp. 825-833.
31	(Zhang *et al.*, 2017)	✓		Zhang, A., Bokel, R., van den Dobbelsteen, A., Sun, Y., Huang, Q. and Zhang, Q. (2017) 'Optimization of thermal and daylight performance of school buildings based on a multi-objective genetic algorithm in the cold climate of China', Energy and Buildings, 139, pp. 371-384.

6. Discussion and Conclusion

This study is part of a wider PhD research on the use of BEPS tools in informing architectural decisions in the early design stages. The study covered twofold objective of the larger research aim through establishing the state of the art in energy modelling tools, to define a categorization and identify recent and emerging trends in their development and application in practice in the last decade (between 2008 and 2019). The methodology adopted a semi-inductive approach, however, the review was framed and limited in accordance with architectural decision-making assistance at the early design stages. The research methodology covered an investigation for the currently available BEPS tools where hundreds of tools were filtered to meet set criteria; 55 tools were found in practice, in addition to 9 in research. Those were then analysed and categorized according to certain development aspects. In terms of targeted user groups, only four tools were found to be mainly targeting architects, while 55% of the tools were aiming to target both architects and engineers. 46% of the listed tools were developed to be used at the conceptual design stage, while the remaining 53% were created to be used for verification purposes later on in the design stage and hence have minimal impact on earlier decisions. BEPS tools were found to have been used in three tool formats with; 55% of the tools to be stand-alone with their own calculation engines; 12 tools provided a plug-in option in other design authoring tools such as Revit, Sketchup, and Rhinoceros to facilitate informing architectural design decisions at early stages and in relation to high design frequency iteration at the early stages, some tools have developed solutions such as the cloud-based simulation to offer real-time results for testing what-if-scenarios instantly. Cloud-simulation was found to be provided by 12 tools.

Regarding the emerging trends in BEPS methods, a filtration process was applied to 730 systematically reviewed publications. 66 publications were then critically reviewed and were found to adopt one or more of the discussed trending methods. As a response to the high level of uncertainty usually accompanied with early design decisions; statistical methods such as sensitivity and uncertainty analysis were found to be trending within 22 publications to quantify the uncertainty level and to calculate the effect different parameters calibration would have on the building's performance. Also for early design decisions making, parametric analysis method was present within 18 publications. The method is usually offered via visual programming platforms where the results of parameter value variations could be visually analysed. In practice, 8 of the listed tools are providing the PA option. Other trending methods for energy performance prediction and building optimization at early stages were found to be AI assisted. Mimicking biological neural networks, ANN would assist in reaching quite accurate energy predictions via machine learning methods through exposure to historical building parameters and their subsequent resulted energy performance. The method is promising in regards to decreasing the performance gap between conventionally simulated and actual results. The main issue is that a lot of data is needed for the calculation model to develop, however once developed, instant results could be calculated. Another AI method is GA mimicking the idea of natural selection to reach an optimized set of parameters through a number of generations. ANN and GA were found to be adopted by 31 studies. Despite being a trend in academia, however, among the 66 tools, only Energy Elephant and cove. Tool were found to be AI assisted.

Emerging trends in the development and application of BEPS in practice are showing increasing concern for aiding early design decisions. This is shown in the increasing number of tools and methods developed for use at the early stage, and tools developed to accommodate architects' requirements. The need for quick and accurate feedback have allowed for new simulation methods as cloud-simulation to emerge. Also, plug-in tools within design authoring tools have increased. Future research shall dig into practice in the UK context to measure the impact of such tools and methods on the ground.

References

Alsaadani, S. (2013) A mixed-methods exploration of non-technical barriers in collaboration for building performance simulation use in architectural decision-making. Cardiff University.

Anderson, J. and Tang, M. (2011) 'Form Follows Parameters: Parametric modeling for fabrication and manufacturing processes'.

Attia, S. (2012) A Tool for Design Decision Making Zero Energy Residential Buildings in Hot Humid Climates. PhD Thesis thesis. Université Catholique de Louvain.

Attia, S., Beltrán, L., De Herde, A. and Hensen, J. (2009) Proceedings of 11th International Building Performance Simulation Association Conference and Exhibition. International Building Performance Simulation Association (IBPSA).

Attia, S. and De Herde, A. (2011) 'Early design simulation tools for net zero energy buildings: a comparison of ten tools', Conference Proceedings of 12th International Building Performance Simulation Association, 2011.

Attia, S., Gratia, E., De Herde, A. and Hensen, J.L.M. (2012) 'Simulation-based decision support tool for early stages of zero-energy building design', Energy and Buildings, 49, pp. 2-15.

Attia, S., Hamdy, M., O'Brien, W. and Carlucci, S. (2013) 'Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design', Energy and Buildings, 60, pp. 110-124.

Augenbroe, G. (1992) 'Integrated building performance evaluation in the early design stages', Building and Environment, 27(2), pp. 149-161.

Bachman, L.R. (2003) Integrated buildings : the systems basis of architecture. Hoboken: Hoboken : J. Wiley & Sons.

BEST (2019) BEST Directory | Building Energy Software Tools. Available at: https://www.buildingenergysoftwaretools.com/ (Accessed: 25/03/2019).

Citherlet, S. (2001) Towards the holistic assessment of building performance based on an integrated simulation approach. Citeseer.

Crawley, D.B., Hand, J.W., Kummert, M. and Griffith, B.T. (2008) 'Contrasting the capabilities of building energy performance simulation programs', Building and Environment, 43(4), pp. 661-673.

De Wilde, P., Augenbroe, G. and Van der Voorden, M. (1999) 'INVOCATION OF BUILDING SIMULATION TOOLS IN BUILDING DESIGN PRACTICE', 6th International IBPSA Conference. Kyoto.

De Wilde, P.J.C.J.d. (2018) Building performance analysis. Hoboken, N.J.: Hoboken, N.J. : Wiley Blackwell.

Engelbrecht, A.P. (2007) Computational intelligence: an introduction. John Wiley & Sons.

Hemsath, T.L. and Bandhosseini, K. (2015) 'Sensitivity analysis evaluating basic building geometry's effect on energy use', Renewable Energy, 76, pp. 526-538.

Hensen, J. (2008) 'On building performance simulation in a changing environment', Building Performance Simulation For Design and Operation.

Hensen, J.L. and Lamberts, R. (2012) Building performance simulation for design and operation. Routledge.

Hopfe, C., Struck, C., Kotek, P., van Schijndel, J., Hensen, J., Plokker, W. and Unit, B. (2007) Proceedings of the 10th IBPSA building simulation conference.

Hopfe, C.J., Struck, C., Harputlugil, G.U., Hensen, J. and De Wilde, P. (2005) IBPSA-NVL Conference.

IEA (2008) Energy efficiency requirements in building codes. France: OECD/IEA. [Online]. Available at: www.iea.org/publications/freepublications/publication/Building_Codes.pdf. (Accessed: 12 January 2018).

Kusuda, T. (1999) 'Early history and future prospects of building system simulation', Proceedings of Building Simulation, 99, pp. 3-15.

Machairas, V., Tsangrassoulis, A. and Axarli, K. (2014) 'Algorithms for optimization of building design: A review', Renewable and Sustainable Energy Reviews, 31, pp. 101-112.

MacLeamy, P. (2004) Collaboration, Integrated Information, and the Project Lifecycle in Building Design and Construction and Operation (WP-1202).

Macumber, D.L., Ball, B.L. and Long, N.L. (2014) Proceedings of the 2014 ASHRAE/IBPSA-USA Building Simulation Conference, Atlanta, GA, USA.

Nguyen, A.-T., Reiter, S. and Rigo, P. (2014) 'A review on simulation-based optimization methods applied to building performance analysis', Applied Energy, 113, pp. 1043-1058.

Nguyen, A.T. and Reiter, S. (2015) A performance comparison of sensitivity analysis methods for building energy models.

Punjabi, S.A. and Miranda, V. (2005) 'Development of an integrated building design information interface', 9th International IBPSA Conference. Montreal, Canada.

Saeed, B.N.S. (2017) Active BIM with artifical intelligence for energy optimisation in buildings.

Saltelli, A., Tarantola, S., Campolongo, F. and Ratto, M. (2004) 'Sensitivity analysis in practice: a guide to assessing scientific models', Chichester, England.

Samuelson, H., Claussnitzer, S., Goyal, A., Chen, Y. and Romo-Castillo, A. (2016) 'Parametric energy simulation in early design: High-rise residential buildings in urban contexts', Building and Environment, 101, pp. 19-31.

Sha, H., Xu, P., Yang, Z., Chen, Y. and Tang, J. (2019) 'Overview of computational intelligence for building energy system design', Renewable and Sustainable Energy Reviews, 108, pp. 76-90.

Shelia J. Hayter, P.A.T., Richard B. Hayter, Ron Judkoff (2001) 'The Energy Design Process for Designing and Constructing High-Performance Buildings', Clima 2000/Napoli 2001 World Congress, 2001.

Suyoto, W., Indraprastha, A. and Purbo, H.W. (2015) 'Parametric Approach as a Tool for Decision-making in Planning and Design Process. Case study: Office Tower in Kebayoran Lama', Procedia - Social and Behavioral Sciences, 184, pp. 328-337.

Weytjens, L. and Verbeeck, G. (2010) 2010 Spring Simulation Multiconference.

Wilde, P.d. and Voorden, M.v.d. (2004) 'Providing computational support for the selection of energy saving building components', Energy and Buildings, 36(8), pp. 749-758.

Yigit, S. and Ozorhon, B. (2018) 'A simulation-based optimization method for designing energy efficient buildings', Energy and Buildings, 178, pp. 216-227.

Single/Dual Variation Approach: A Novel Bridge System Identification Method Based on Static Analysis and Parallel Simulation

Fangzheng Lin[1,] *, Raimar J. Scherer[1], Tom Grille[1], Markus Petschacher[2]

[1] Institute of Construction Informatics, TU Dresden, Germany

[2] Petschacher Software- und Projektentwicklungs GmbH, Austria

* email: fangzheng.lin@tu-dresden.de

Abstract

Bridge health assessment is an interdisciplinary area of interest for various engineering fields. System identification can applied to address this assignment, which has been developed for decades. Supported by the modern bridge monitoring system, conventional system identification methods are primarily associated with modal analysis, since the natural frequencies are able to be obtained from the monitored data. Generally, the research focuses are located in simulation results evaluation and monitoring system optimization. The simulation process for system identification is still not prominently improved. This paper proposes a novel simulation based system identification method integrated with parallel processing. Single Variation Approach (SVA) and Dual Variation Approach (DVA) compose this method. In both sub approaches, (quasi-)static simulation is in a parallel processing environment executed instead of dynamic analysis to achieve bridges' responses. In principle, SVA requires lots of monitoring points along the bridge alignment, so that each monitoring section in a bridge can be identified. DVA exploits the enormous traffic load data delivered by Bridge Weigh-In-Motion (BWIM) system. As consequence, the demand of monitoring points in DVA declines significantly, nevertheless, the system identification hereby works still effectively. Five scenario cases are studied to validate the proposed method and to explore its features.

Keywords: system identification, bridge damage, FEM, static analysis, parallel processing

1. Background

The field of system identification uses statistical methods to build mathematical models of dynamical systems from measured data. Since decades, the application of system identification in structure damage detection has demonstrated a wide spectrum. Brownjohn studied ambient vibration of tall buildings to complete system identification by the means of modal analysis (Brownjohn, 2003). Researchers also attempted to compose different algorithms to improve system identification quality. Genetic Algorithm (GA) and Support Vector Machine (SVM) were combined to detect bridge damage (Liu & Jiao, 2011). Convolutional Neural Network (CNN) becoming pretty popular in the last five years was successfully verified to estimate the actual amount of structural damage as well (Abdeljaber et al., 2018; Abdeljaber, Avci, Kiranyaz, Gabbouj, & Inman, 2017). Overall, the mainstream relevant researches focus on combining structural system identification with diverse algorithms or optimizing these algorithms. Meanwhile, dynamical analysis methods including modal analysis are the most widely used method to simulate system assumptions. As the world steps into the epoch of Industry 4.0, several informatics techniques such as cloud computing, virtual reality, internet of things, etc. are already maturely developed for the integration in Architecture Engineering and Construction industry. This paper proposes a novel simulation based system identification method. This method takes advantage of the principle of parallel computing to curtail simulation duration of the entire identification process. Additionally, static analysis supported by a modern structural monitoring system rather than structural dynamics is executed to identify the local structural damage. The proposed system identification method consists of two sub approaches; both are validated and studied through case study.

2. Bridge Weigh-In-Motion

Bridge Weigh-In-Motion (BWIM) developed by Moses in 1979 measures bridge deformation at ceiling during truck passage and evaluates axle loads beside other characteristics (Petschacher, 2010). The quality requirements have been formulated in project COST 323. In order to get a high accuracy two requirements, which have to be fulfilled, sensitive sensors and appropriate hardware with high sampling rate producing appropriate resolution of signal smaller than 1 μs. Given a truck with three axles passes over a bridge then two times number of axles of unknown has to be solved, i.e. velocity, axle distances and weights. Basis for this type of analysis forms a pre-estimated influence line of the particular bridge. Each analysis of an event starts with estimating velocity, detecting axles, and solving finally a set of equations coming from strain records over time. The estimated axle weights are related to results from a calibration phase at that bridge. A sufficient set of different calibration trucks runs form the basis for accurate results. A BWIM system for production usage involves a lot of quality checks during analysis and is combined with artificial intelligence components to use previous experience in estimating good starting values. BWIM is utilized to collect all load events on different bridge lanes. Road administration is interested in fraction of overloads, extreme loadings, or truck traffic amount, engineers may extrapolate observed events to extreme value statistics and estimate design value for mid-span moment. Measurement combined with sensors of load cycles or bending curvature may complete pictures of the bridge. Figure 1 demonstrates a few sensors and the sensor distribution in a bridge monitoring system.

Measuring Value	Standard	Ring	Bending	Gauge	Rosette	Acceleration	Laser
Deflection	O	O	O	O	O	O	OOO
Curvature	O	OO	OOO	O	O	O	O
Strain	OOO	OOO	O	OOO	O	O	O
Acceleration	O	O	O	OO	O	OOO	O
Inclination	O	O	O	O	O	OOO	O
Distance	O	O	O	O	O	O	OOO
Shear	O	O	O	O	OOO	O	O
Rel. displacement	O	O	O	O	O	OOO	OOO
Frequency	OO	OOO	O	OO	O	OOO	O

OOO = highly suitable, OO = suitable, O = unsuitable

Figure 1: Sensors Installed in a Bridge and Sensors Applied in a Bridge Monitoring System

3. Bridge System Identification

3.1 Stiffness Assumption

The real stiffness reduction β of bridge segments ought to be an irrational number, i.e. there are infinitive numbers behind the decimal point. Nevertheless, in civil engineering practice, it is meaningless to detect the stiffness reduction with an extremely high precision, since material laws, structural analysis algorithms and loads all do not reach that accuracy. In order to avoid the over-fitting problem, this system identification approach aims at detecting the current stiffness state $\alpha\ (= 1 - \beta)$ in ten continuous separated intervals with distance 0.1 between 0 and 1 (Table 1). The bottom edge 0.001 in the first interval instead of 0 prevents simulation results from singularity effect due to a complete stiffness loss in bridge segment.

Table 1: Assumption Values and Intervals

Interval 1	Interval 2	Interval 3	Interval 4	Interval 5
$[0.001, 0.1]$	$(0.1, 0.2]$	$(0.2, 0.3]$	$(0.3, 0.4]$	$(0.4, 0.5]$
Interval 6	Interval 7	Interval 8	Interval 9	Interval 10
$(0.5, 0.6]$	$(0.6, 0.7]$	$(0.7, 0.8]$	$(0.8, 0.9]$	$(0.9, 1.0]$

3.2 Damage Modelling

The repercussions of concrete cracks, which are the major typical damage in bridges, can be reflected through stiffness reduction. Christides and Barr (1983) proposed the one-dimensional theory of cracked Bernoulli-Euler beams to describe this phenomenon. Since then, the mathematical model of concrete crack has been developed intensively for decades (Shah, 1997). Pursuant to the theoretical researches, Firswell and Penny (2002) transformed the mathematical crack model into the numerical computation (Figure 2).

According to the theory of FEM and the modelling philosophies in FEA software, an efficient solution to addressing damage modelling is altering the corresponding parameters in input models of FEA software (Lin et al., 2019). For instance, the reflection of concrete crack could either be a rough factor of the entire stiffness value or weakening some specific material features at the damaged position in the bridge model.

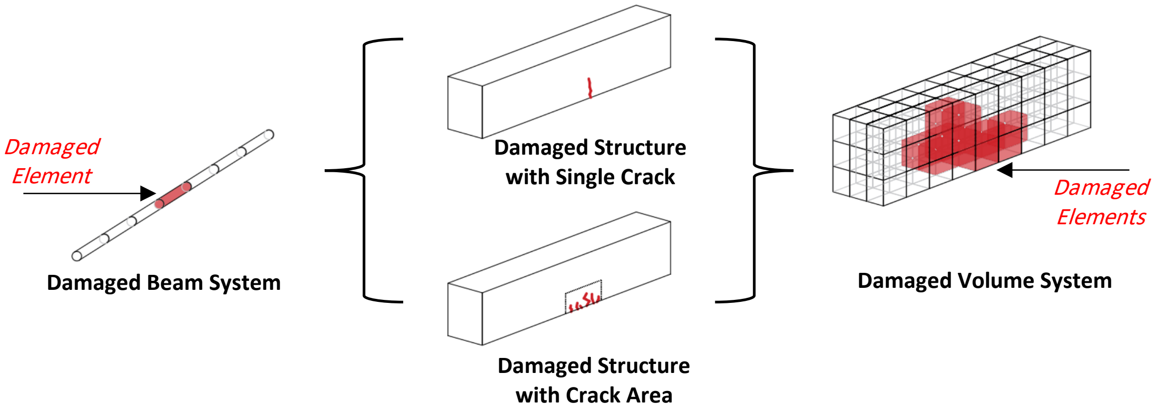


Figure 2: Crack Modelling in FEA Software

3.2.1 System Variants and Parallel Simulation

Figure 3 demonstrates the workflow of the proposed system identification method containing Single Variation Approach (SVA) and Dual Variation Approach (DVA). Both approaches will be described beneath with more details. The concept system variants in SVA means simplify model variants, parameters (e.g. bending stiffness) of which are modified by the initial values from sampling in section 2.1. Besides model variants, system variants in DVA involve load variants as well.

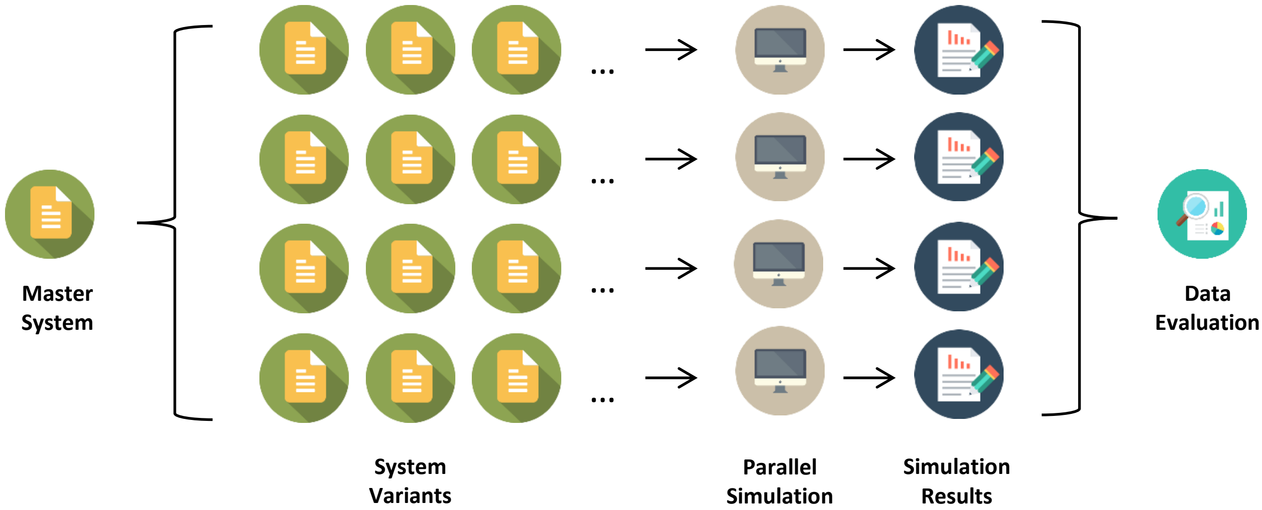


Figure 3: A System Identification Workflow of SVA and DVA

Copious system variants are requested to be generated. The quantity of model variants could reach a giant order of magnitude theoretically, e.g. one million or much larger. To a computer with single processing, the probable overloaded work will cause a lengthy computing duration and even system crash. Therefore, it makes sense to utilize parallel computing technique to handle this problem.

Parallel computing is a type of computation in which many calculations or the executions of processes are carried out simultaneously. As the concept of Big Data arises, parallel simulation or parallel processing appears with an increasing frequency. This technique can either be implemented in one multi-core computer with several parallel coroutines, or be realized through servers in grid or cloud. During the simulation based system identification integrated with parallel processing, system variants are grouped according to the parallel processing quantity, subsequently executed separately and simultaneously, so that the entire simulation duration decreases significantly.

3.2.2 Residual Sum of Squares

A Residual Sum of Squares (RSS) is a statistical technique used to measure the amount of variance in a data set that is unexplained by a regression model. RSS is a measure of the amount of error remaining between the regression function and the data set. A smaller RSS figure represents a regression function that explains a greater amount of the data (Desai, 2011).

RSS is defined by the following function:

$$RSS = \sum_{i=0}^{n}(\epsilon_i)^2 = \sum_{i=0}^{n}[y_i - f(x_i)]^2 ,$$

where n indicates set number of count, y_i and $f(x_i)$ represent the value sets that need to be compared. In statistics, RSS is a basic measure of the discrepancy between the data and an estimation model.

3.2.3 Single/Dual Variation Approach

Through the modern bridge monitoring techniques, engineers are capable to obtain the real-time traffic load data and the corresponding deflection at monitoring points with certain accuracy from captured sensor data. Hence, the Single Variation Approach (SVA) is proposed to address system identification using quasi-static analysis. By means of SVA, system variants are the single argument where variation takes place. The response of damaged bridges due to one load case are then calculated. Afterwards, the simulation results serve for the comparison with deflections from the monitoring data.

The equation of quasi-static analysis is:

$$\boldsymbol{K}\cdot\boldsymbol{u}=\boldsymbol{f};$$

the bridge response vector u here can be computed:

$$\boldsymbol{u}=\boldsymbol{K}^{-1}\cdot\boldsymbol{f},$$

where $\boldsymbol{K}$ means the stiffness matrix with reduced/damaged stiffness values, $\boldsymbol{f}$ is the load vector describing one load case. In Dual Variation Approach (DVA), the equation of quasi-static analysis takes advantage of more load cases:

$$\boldsymbol{K}\cdot\boldsymbol{U}=\boldsymbol{F}.$$

In the equation above, $\boldsymbol{F}$ is not a vector any more but a matrix consisted of various non-linear related load vectors:

$$\boldsymbol{F}=\ [\boldsymbol{f_1}\,\boldsymbol{f_2}\dots\boldsymbol{f_i}\dots\boldsymbol{f_n}\,]=\begin{bmatrix}\begin{bmatrix}f_{11}\\f_{12}\\\dots\\f_{1j}\\\dots\\f_{1m}\end{bmatrix}\begin{bmatrix}f_{21}\\f_{22}\\\dots\\f_{2j}\\\dots\\f_{2m}\end{bmatrix}\dots\begin{bmatrix}f_{i1}\\f_{i2}\\\dots\\f_{ij}\\\dots\\f_{im}\end{bmatrix}\dots\begin{bmatrix}f_{n1}\\f_{n2}\\\dots\\f_{nj}\\\dots\\f_{nm}\end{bmatrix}\end{bmatrix},$$

Because of that, the matrix of deformation $\boldsymbol{U}$ having the identical size of $\boldsymbol{F}$:

$$\boldsymbol{U}=\ [\boldsymbol{u_1}\,\boldsymbol{u_2}\dots\boldsymbol{u_i}\dots\boldsymbol{u_n}\,]=\begin{bmatrix}\begin{bmatrix}u_{11}\\u_{12}\\\dots\\u_{1j}\\\dots\\u_{1m}\end{bmatrix}\begin{bmatrix}u_{21}\\u_{22}\\\dots\\u_{2j}\\\dots\\u_{2m}\end{bmatrix}\dots\begin{bmatrix}u_{i1}\\u_{i2}\\\dots\\u_{ij}\\\dots\\u_{im}\end{bmatrix}\dots\begin{bmatrix}u_{n1}\\u_{n2}\\\dots\\u_{nj}\\\dots\\u_{nm}\end{bmatrix}\end{bmatrix},$$

where m is the total quantity of degrees of freedom of the system, n complies with the number of load cases. According to the numbers and categories of data from the monitoring system, the observed bridge responses $\boldsymbol{u^r}/\boldsymbol{U^r}$ corresponding to the monitored values $\boldsymbol{u^m}/\boldsymbol{U^m}$ are filtered out from the entire simulation results for the purpose of system identification. RSS briefly introduced in section 4.4 is variated in the proposed approach and utilized to assess matching degree of system variants:

$$RSS=\sum_{i=1}^{n}|d\boldsymbol{u_i}|\ =\ \sum_{i=1}^{n}[\sqrt{\sum_{j=1}^{m}\left(du_{ij}\right)^2}]=\ \sum_{i=1}^{n}[\sqrt{\sum_{j=1}^{m}\left(u_{ij}^{r}-u_{ij}^{m}\right)^2}].$$

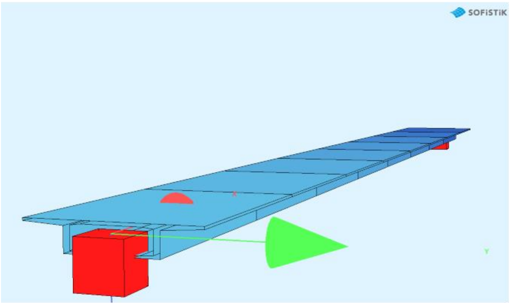
The RSS here is finally calculated as the sum of the error vector norms, so that the impact from positive or negative errors can be prevented. Under the assumption of SVA where n is equal to one, there ought to be however many monitoring data of bridge responses. Therefore, SVA is solely another application of the conventional system identification methods with static calculation and parallel simulation. DVA, in which n in the equations above indicates the number of load cases, is designed to address the scenarios with limited sensor installation places but comprehensive various load cases.

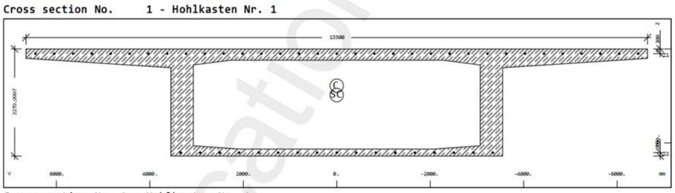
Theoretically, SVA works as a system identification method with strong dependence with monitoring data. In other words, the monitoring system delivering enough data of bridge responses for error calibration in result comparison is a prerequisite for that SVA functions ideally. In the case of limited monitoring data in engineering practice, DVA, an alternative solution, attempts to implement a vast of traffic load from monitoring system in order to identify the best-fit system variants. Several examples are demonstrated beneath for understanding and validation.

3.3 Case Study

3.3.1 General

A master bridge model with constant cross sections is applied to validate SVA and DVA. The freedoms of displacements in three spatial dimensions at both bridge ends are constrained. The isometry, cross section and features of the test bridge are displayed in Figure 4. A 2D FE-system is built by program language Julia based on the bridge material and mechanical parameters. The vertical deflections at each node due to vertical loads are the values of major interest. Considering that, there could be more than one million system variants executed in simulation, 20 parallel processes of Julia established in a local computer are utilized to reduce the entire simulation duration significantly of the designed master bridge in Figure 4.





Cross section No. 1 - Hohlkasten Nr. 1

Cross Section Area [A]	6.5934 m²		Bridge Length [L]	16 m
E-Modulus [E]	34077×10^6 N/m²		Dead Load [q]	164.835 kN/m
Moment of Inertia [I_y]	4.639 m⁴			

Figure 4: The Bridge Example for Case Study

3.3.2 Single Variation Approach

Figure 5 shows two scenario cases. In Case 1, the bridge system meshed by four beam elements owns three monitoring points and therefore four monitoring sections. Based on the ten sampling groups at each monitoring sections, there are 10,000 system variants in total. The principle of FEM implies that the more finely a system is meshed, the more precise solutions show up after simulation. Hence, the static system in Case 2 is refined by 8 beam elements but still contains 4 monitoring sections in order to observe influence from a more finely meshed monitoring section. As introduced in section 2.5, SVA functions with dependence on monitoring points. One monitoring section either can be an element or consists of several elements for a relatively accurate simulation. The quantity of system variants in SVA corresponds exclusively to the number of monitoring sections. In other words, the bridge system in Case 2 has 10,000 system variants, where each element in one monitoring section has the same stiffness assumption. For both cases in Figure 5, the load vector concerns the combined effect of bridge dead load q and the external single load F.

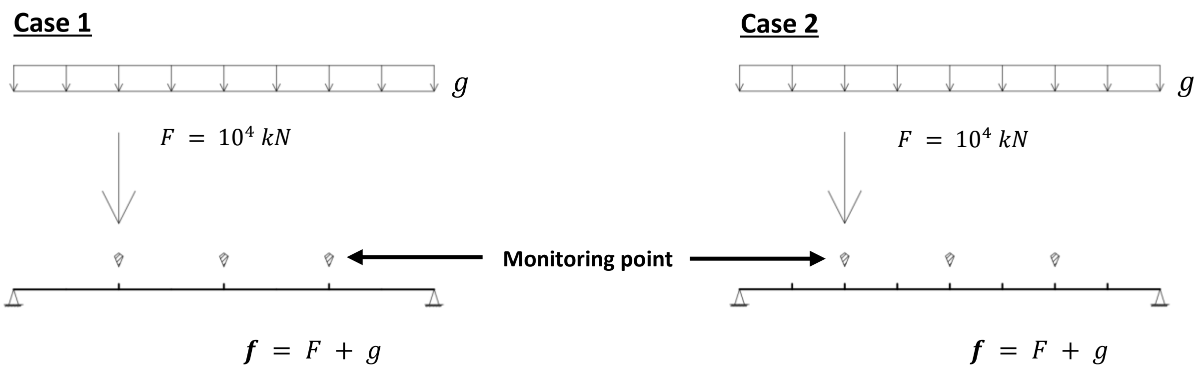


Figure 5: The Bridge Static System for Scenario Case 1 and 2

For theoretical study of system identification, the bridge response based on the assumed stiffness stats serves as the assumed monitoring data. Stiffness assumption (S.A. in Table 2) indicates for instance the first monitoring section as well as element 1 in Case 1 has 70% stiffness reduction, so that its current stiffness state amounts to 0.3. The first monitoring section in Case 2 is also assumed to have a 70% stiffness loss, therefore, the belonging elements (Element No. 1 and No. 2) both have 30% of the original stiffness.

Table 2: Simulation Results of SVA for Case 1 and Case 2

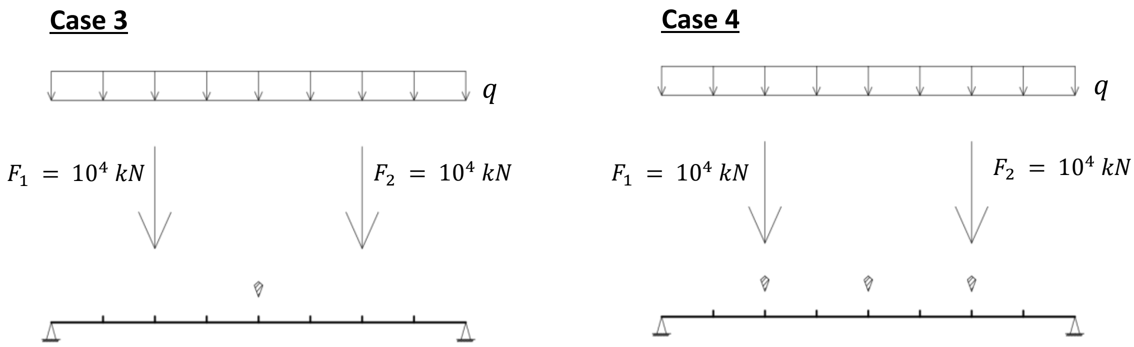
	Case 1					**Case 2**							
E-No.*	**1**	**2**	**3**	**4**		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
S.A.	0.3	0.4	0.2	0.6		0.3	0.3	0.4	0.4	0.2	0.2	0.6	0.6
1st B.F.S.	0.3	0.4	0.2	0.6		0.3	0.3	0.4	0.4	0.2	0.2	0.6	0.6
S. A.	0.38	0.43	0.22	0.67		0.38	0.38	0.43	0.43	0.22	0.22	0.67	0.67
1st B.F.S.	0.3	0.7	0.2	0.7		0.4	0.4	0.4	0.4	0.6	0.6	0.5	0.5
2nd B.F.S.	0.4	0.4	0.2	0.7		0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5
3rd B.F.S.	0.4	0.4	0.3	0.6		0.4	0.4	0.4	0.4	0.3	0.3	0.6	0.6

***E-No. :** Element Number**; S.A. :** Stiffness Assumption**; B.F.S. :** Best-Fit System

If the stiffness assumption has one decimal place, the first best-fit system variant is exact the assumed system. In this way, the system can be identified with no error. If the stiffness is more realistically assumed, e.g. the assumption with two decimal places, the identification results ordered ascendingly by the errors performs complicatedly. The first best-fit system fails to identify all the elements of the bridge system. Thus for the purpose of system identification, the first several best-fit systems are request to be analyzed comprehensively to assess the interval of system stiffness state. Even so, identification works with some error. Considering that the assumption should be irrational numbers, SVA is capable to identify the system with a relative weak accuracy.

3.3.3 Double Variation Approach

Two scenario cases in Figure 6 are studied to validate DVA in system identification, Case 3 has one monitoring point, eight beam elements, four monitoring sections, while three monitoring points are set in Case 4 having the same number of elements and monitoring points. So that 10,000 system variants are executed in parallel simulation. The load matrix F including four different load cases is on the right side of the static equation. The influence of monitoring point quantity on identification quality is hereby observed as well.



Case 3:

$$\boldsymbol{F} = [\,\boldsymbol{f}_1 \;\; \boldsymbol{f}_2 \;\; \boldsymbol{f}_3 \;\; \boldsymbol{f}_4\,]$$
$$\boldsymbol{f}_1 = F_1 \qquad \boldsymbol{f}_2 = F_2$$
$$\boldsymbol{f}_3 = F_1 + q \qquad \boldsymbol{f}_4 = F_2 + q$$

Case 4:

$$\boldsymbol{F} = [\,\boldsymbol{f}_1 \;\; \boldsymbol{f}_2 \;\; \boldsymbol{f}_3 \;\; \boldsymbol{f}_4\,]$$
$$\boldsymbol{f}_1 = F_1 \qquad \boldsymbol{f}_2 = F_2$$
$$\boldsymbol{f}_3 = F_1 + q \qquad \boldsymbol{f}_4 = F_2 + q$$

Figure 6: The Bridge Static System for Scenario Case 3 and 4

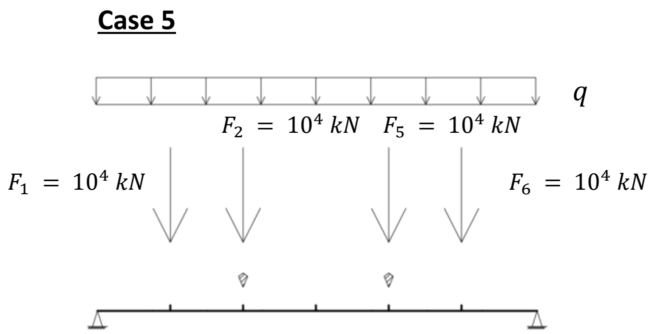
It is apparent to see that DVA presents a stronger system identification capability than SVA under the stiffness assumption having two decimal places, with which the first best-fit system variant in Table 3 is basically in accordance. Meanwhile the given two scenario cases in Table 3 do not satisfy identifying the system exactly assumed by stiffness with three decimal places. Considering a set of the first best-fit systems, DVA under four load cases offers notwithstanding a rough identification quality. Because the bridge monitoring system is able to deliver surplus traffic load data, an optimization possibility lies in using more traffic load cases for error dwindling. Hence, a static system with 12 load cases (Case 5 in Figure 7) is supposed to be simulated to explore the relationship between load cases and identification accuracy.

Table 3: Simulation Results of DVA for Case 3 and Case 4

	Case 3									**Case 4**							
E-No.*	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
S.A.	**[0.38 0.38 0.43 0.43 0.22 0.22 0.67 0.67]**																
1st B.F.S.	**0.4**	**0.4**	**0.4**	**0.4**	**0.2**	**0.2**	**0.7**	**0.7**		**0.4**	**0.4**	**0.4**	**0.4**	**0.2**	**0.2**	**0.7**	**0.7**
2nd B.F.S.	**0.4**	**0.4**	**0.4**	**0.4**	**0.5**	**0.5**	**0.4**	**0.4**		**0.4**	**0.4**	**0.4**	**0.4**	**0.7**	**0.7**	**0.2**	**0.2**
3rd B.F.S.	**0.6**	**0.6**	**0.3**	**0.3**	**0.5**	**0.5**	**0.3**	**0.3**		**0.5**	**0.5**	**0.3**	**0.3**	**0.5**	**0.5**	**0.4**	**0.4**
S. A.	**[0.382 0.382 0.435 0.435 0.221 0.221 0.678 0.678]**																
1st B.F.S.	**0.5**	**0.5**	**0.4**	**0.4**	**0.5**	**0.5**	**0.3**	**0.3**		**0.5**	**0.5**	**0.4**	**0.4**	**0.8**	**0.8**	**0.2**	**0.2**
2nd B.F.S.	**0.5**	**0.5**	**0.4**	**0.4**	**0.2**	**0.2**	**0.6**	**0.6**		**0.4**	**0.4**	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**
3rd B.F.S.	**0.3**	**0.3**	**0.5**	**0.5**	**0.2**	**0.2**	**0.8**	**0.8**		**0.4**	**0.4**	**0.4**	**0.4**	**0.2**	**0.2**	**0.7**	**0.7**
***E-No. :** Element Number**; S.A. :** Stiffness Assumption**; B.F.S. :** Best-Fit System																	

The scenario Case 5 is a bridge static system with two monitoring points installed. The static system is meshed by six beam sections, whereby a monitoring section is equal to a beam element. Thus, there are on million system variants in total since ten values are sampled to estimate each monitoring section. According to the result analysis from cases in Figure 4, 12 load cases including different load locations and load values are of concern in this part of case study.

The first six best-fit system variants under the stiffness assumption with three decimal places are listed in Table 4, where the left part concerns the effect of 10 load cases, the right of 12 load cases. Compared to the corresponding results in Table 3, more load cases is indeed advantageous to system identification. The first two best-fit system variants from Case 5 draw near obviously the assumption, especially if the assumption is situated around the edges of the sampling interval from zero to one. In terms of the number of load cases, the ordered system variants in right table part for 12 load cases do not supply a better identification accuracy than the system variants for ten load cases. It follows that simulation deliberating more load cases brings more effective system identification. At the same time, a collection of redundant load cases cannot lead to an extremely exact identification quality. Hence, an appropriate number of load cases is requested to be determined.



$\boldsymbol{f}_1 = F_1$	$\boldsymbol{f}_7 = F_5 + q$
$\boldsymbol{f}_2 = F_2$	$\boldsymbol{f}_8 = F_6 + q$
$\boldsymbol{f}_3 = F_1 + q$	$\boldsymbol{f}_9 = F_5 + F_1 + q$
$\boldsymbol{f}_4 = F_2 + q$	$\boldsymbol{f}_{10} = F_6 + F_2 + q$
$\boldsymbol{f}_5 = F_5$	$\boldsymbol{f}_{11} = F_5 + F_2 + q$
$\boldsymbol{f}_6 = F_6$	$\boldsymbol{f}_{12} = F_6 + F_1 + q$

Figure 7: The Bridge Static System for Scenario Case 5

Table 4: Simulation Results of DVA for Case 5

	f = f1 + f2 + … + f9 + f10							f = f1 + f2 + … + f11 + f12					
E-No.*	**1**	**2**	**3**	**4**	**5**	**6**		**1**	**2**	**3**	**4**	**5**	**6**
S.A.	[0.213 0.425 0.194 0.387 0.642 0.927]												
1st B.F.S.	0.2	0.6	0.2	0.5	0.5	0.9		0.2	0.6	0.2	0.5	0.5	0.9
2nd B.F.S.	0.2	0.5	0.2	0.5	0.6	0.9		0.2	0.8	0.2	0.7	0.3	0.9
3rd B.F.S.	0.2	0.8	0.2	0.7	0.3	0.9		0.2	0.7	0.2	0.6	0.4	0.9
4th B.F.S.	0.2	0.9	0.2	0.6	0.3	0.9		0.2	0.5	0.2	0.5	0.6	0.9
5th B.F.S.	0.2	0.7	0.2	0.5	0.4	0.9		0.2	0.7	0.2	0.5	0.5	0.9
6th B.F.S.	0.2	0.5	0.2	0.4	0.8	0.9		0.2	0.6	0.2	0.5	0.6	0.9

*__E-No. :__ Element Number; **S.A. :** Stiffness Assumption; **B.F.S. :** Best-Fit System

3.4 Conclusion and Discussion

As the concept of Big Data arises, massive simulation through parallel processing will show its promising perspective in system identification. The proposed novel system identification method is capable to replace the conventional ones, in which structural dynamic analysis is used to be executed. This paper discuses the feasibility of this method, which has been validated by case study. Both two sub approaches, receptively SVA and DVA, in the proposed method can address the system identification problem. SVA requires a strong data support from a bridge monitoring system. Thus identifying the damage state of each monitoring section works in this case. In addition, finer meshing in monitoring sections does not assist SVA to obtain results that are more reliable. In DVA, the contribution of structural health monitoring to system identification is diminished. Meanwhile, the technique of BWIM is integrated to collect abundant load data of vehicles. By means of DVA, either a monitoring section with elements or a finite element can be regarded as an identification unit. Despite of fewer monitoring points than SVA, DVA brings more plausible system identification results. Evaluating simulation results by RSS performance a rougher accuracy with relative large errors. The chosen best-fit system variants cannot always successfully identify the stiffness statue of all finite elements based on the assumption in Table 1. Therefore, other classification algorithms deserve to be researched to mitigate this shortcoming.

3.5 Implementation in Research Project wiSIB

The acronym wiSIB stands for the German translation of project name “A Simulation and Knowledge Based System Identification Method”. This research project chases two main objectives: 1) establishing a knowledge database describing as many categories of bridge damage as possible; 2) developing a system identification process integrated with parallel computing.

Theoretical argumentation of the proposed system identification methodology from project wiSIB is displayed in this paper. The entire process shown in Figure 4 ought to be realized based on the particular requirements in wiSIB. With the support of FEA software, more kinds of bridge responses can be computed to identify a system as long as the developing bridge monitoring technique offers more direct or indirect useful measurements. Nevertheless, the implementation is conditional. The majority of commercial FEA software must run with legal licenses. While the software is virtually duplicated in parallel processing, either its licenses with unique ID-key are usually uncopiable or these license copies are invalid. To build a parallel processing environment, end users have to pay for a new license for each single coroutine. Although the coroutines of parallel processing can technically increase to a copious number, the cost of software licenses in such circumstance would not be affordable. As a consequences, a grid/could simulation platform based on FEA software functions with confinement of capacity and performance. Therefore, it is meaningful to optimize the Single/Dual Variation Approach to reach the goal of system identification in the orientation of decreasing the operation stress in platform through initiating fewer system variants.

Acknowledgements

The authors would like to acknowledge the support of the Federal Ministry of Education and Research of Germany to the funding of the project wiSIB, No. 01IS16031C.

References

Abdeljaber, O., Avci, O., Kiranyaz, M. S., Boashash, B., Sodano, H., & Inman, D. J. (2018). 1-D CNNs for structural damage detection: Verification on a structural health monitoring benchmark data. Neurocomputing, 275, 1308–1317. https://doi.org/10.1016/j.neucom.2017.09.069

Abdeljaber, O., Avci, O., Kiranyaz, S., Gabbouj, M., & Inman, D. J. (2017). Real-time vibration-based structural damage detection using one-dimensional convolutional neural networks. Journal of Sound and Vibration, 388, 154–170. https://doi.org/10.1016/j.jsv.2016.10.043

Bornn, L., Farrar, C. R., & Park, G. (2010). Damage detection in initially nonlinear systems. International Journal of Engineering Science, 48(10), 909–920. https://doi.org/10.1016/j.ijengsci.2010.05.011

Brownjohn, J. M. W. (2003). Ambient vibration studies for system identification of tall buildings. Earthquake Engineering & Structural Dynamics, 32(1), 71–95. https://doi.org/10.1002/eqe.215

Desai, Y. M. (2011). Finite Element Method with Applications in Engineering. Pearson Education India.

Furukawa T., Ito M., Izawa K., & Noori M. N. (2005). System Identification of Base-Isolated Building using Seismic Response Data. Journal of Engineering Mechanics, 131(3), 268–275. https://doi.org/10.1061/(ASCE)0733-9399(2005)131:3(268)

Kim, Y., Chong, J. W., Chon, K. H., & Kim, J. (2012). Wavelet-based AR–SVM for health monitoring of smart structures. Smart Materials and Structures, 22(1), 015003. https://doi.org/10.1088/0964-1726/22/1/015003

Koutromanos, I. (2018). Fundamentals of Finite Element Analysis: Linear Finite Element Analysis. John Wiley & Sons.

LCPC. (1999). COST 323. European Weigh-in-Motion Specifications Version 3.0.

Liu, H.-B., & Jiao, Y.-B. (2011). Application of genetic algorithm-support vector machine (ga-svm) for damage identification of bridge. International Journal of Computational Intelligence and Applications, 10(04), 383–397. https://doi.org/10.1142/S1469026811003215

Petschacher, M. (2010). Bridge-Weigh-in-Motion. Bundesministerium Für Verkehr, Innovation Und Technologie, 5921.

Ricardo, H. (2009). A Modern Introduction to Linear Algebra. CRC Press.

Reading Urban Spaces through Agent-Based Simulation in Light of Mobile ICT

Aminreza Iranmanesh[1*], Resmiye A. Atun[2]

[1]Department of architecture, Eastern Mediterranean University, Famagusta, North Cyprus, Turkey

[2]Department of architecture, Eastern Mediterranean University, Famagusta, North Cyprus, Turkey

*Email: aminreza.iranmanesh@emu.edu.tr

Abstract

This study aims to provide an empirical way for the utilization of geotagged social media into urban pedestrian movement simulation as a way to improve the design, planning, and development. During the past decade, the advent of Information and Communication Technologies (ICT) into the everyday life of people has restructured some of the fundamental interactive aspects of cities. People's perception of cities is being reconfigured by the constant interactions that pass through connected mobile devices. This paper aims to explore new possibilities for the integration of social media into a visibility based pedestrian agent simulation. Four staged of data collection and analysis is proposed: First, the paper establishes a baseline by conducting a thorough systematic observation of the case study, the number of pedestrians were counted for 72 segments of an organic urban pattern. Second, a visibility-based agent simulation for predicting pedestrian movement patterns is conducted. This phase uses the morphological dimensions of space as the input and predicts the potential points of interest based on the agent's field of view. Third, the geographically tagged social media interactions from a limited timeframe were collected and analysed. Twitter has been used for reading volunteer pedestrian documentation of urban spaces. Fourth, the agent-based model output and tweet count were used in a regression model exploring the predictability of the actual pedestrian count (first phase). Finally, the results of different regression analysis were compared, and the outcome shows improvement in the simulation when Twitter data was included in the model, indicating that 69% of all pedestrian movements can be explained by the improved model. The outcome provides a reading into urban areas of interest for the pedestrian that is being formed by both visual accessibility and people's interaction through social media.

Keywords: Visual graph analysis, agent-based pedestrian simulation, ICT, Urban design, social media, mixed methods

1. Introduction

Mobile ICT has transformed the role of people to the recorders and broadcasters of the urban narrative. The active choice of citizens to take part in urban spaces are being influenced by others' activities on social media. Since the socio-economical aspects of urban network and land-use are dependent on the flow of people, it could be argued that mobile ICT plays a critical role in the resilience and socio-economic sustainability of urban spaces. Although the simulation of people's movement has been a significant part of the urban studies in the past decade, few have paid attention to the integration of social media data into those simulations. Accordingly, the power of the active interaction between people and city could be harvested for providing a more comprehensive perspective on design, planning, and development of contemporary cities. The process of reading, diagnostics, and proposal for city spaces must be mindful of the emerging layers of data. In the past century, urban-related research has shifted toward analytical approaches trying to address the increasing complexity of cities. The increase in computational power and accessibility to new sources of data has revolutionised the research on cities. In this paper, we address one of the emerging methods for exploring socio-spatial structures of cities: the visibility based agent simulation. Understanding the flow of pedestrian movement is a critical aspect of urban design and planning as it is closely related to the Microeconomics and vitality of public spaces. The paper uses the suggested algorithm by Turner and Penn (2002) and tries to explore new methodological possibilities by introducing a new layer of ICT data into the model.

2. Agent-based Model

An agent-based simulation is a powerful method for assessing and understanding complex spatial structures according to the human perceptual process of decision making while moving. The method was established by Turner and Penn (2002) and it is grounded on the theory of ecological perception set forth by Gibson (1979). Gibson (1979) established the theory of ecological perception in which he suggested a bottom-up approach toward the visual and information processes of the environment by animals and humans. He creates the concept of “affordance” as a set of potential opportunities that environment offers; he fundamentally describes it as the walkable/visible plane or a surface that affords the movement (Gibson, 2014). In other words, the affordance is the potential actions, or the availability of movement that space creates for the actors (Norman, 1999). This framework provides new possibilities in exploring complex spatial systems because the bottom-up processing of environment enables analytical models which are less bounded by the complex contextual parameters of human cognition.

Accordingly, Turner and Penn (2002) proposed an agent-based model that incorporates the visibility affordance of the space as the major factor in movement. The agent-based model follows a very simple rule that seeks to understand the complex nature of human movement; people tend to travel toward the further accessible space base on their current position (Koutsolampros & Varoudis, 2017). the method is called “Exosomatic Visual Architecture: EVA” (Turner & Penn, 2002) and it explains the process of decision making and movements by the virtual agents. EVA is comprised of the following steps:

- The spaces that support unrestricted movements (and visible) are broken down into a basic mosaic of cells (gates). The dimension of these cells is often considered 0.75 x 0.75m because it is the average length of steps while walking (Turner, Doxa, O'sullivan, & Penn, 2001) (Figure 1: a&b).
- The visual graph analysis (VGA) is conducted, VGA explores the degree of visibility for each part of the space from all other parts. VGA represents the “intensity of intervisibility” among all cells in the plane of sight/movement (Karimi, 2012). Here we take into account that a cell must be both visible and accessible, this is following Gibson’s theory of affordance (Figure 1:c).
- Aa agent is randomly placed in the field; each agent is assigned a field of view that can be adjusted according to the parameters of the study. In order to enable the random movement of agents, the field of view is further broken down to 32 possible bins each covering approximately 11 degrees (Koutsolampros & Varoudis, 2017) (Figure 1:d). The most efficient applied field of view is considered 170 degrees or 15 bins (Turner & Penn, 2002).
- The agent chooses a destination from the available field of view (Figure 1: e).
- The agent moves n number of steps toward the selected destination, n can be defined by the research, n=0 means the agent picks a new destination every single step, and a higher n means that the agent does not change the target before reaching the initially selected target. According to Turner and Penn (2002), n=3 gives shows the best outcome when compared to the actual movement of people in the space, meaning that the agent takes 3 steps and then chooses a new destination. During this process If at any point the agent faces an obstacle (wall, corner, other agents) it randomly turns 90 degrees, if the movement is still not possible, the agent chooses a new destination.
- The agent repeats the cycle of steeping toward randomly selected destinations from the field of view for a given number before being removed. The number of steps could be defined by the

parameters of the study, for instance, how much people are willing to walk in a given context? or How large is the area of the study.

- The same procedure is repeated for a given number of agents. And the number of encounter with each cell is presented on the map (the random next step map, Figure 1:f&g).
- Turner and Penn (2007) proposed an alternative process for selecting destinations in which the decision is weighted by the longest available line of sight arguing that it resembles more similarities with how people pick a destination (Figure 1:h).

The initial studies show that the EVA agent base simulation can explain 50% to 75% of natural pedestrian movement (Penn & Turner, 2002; Turner & Penn, 2002), Jiang and Jia (2011) report a correlation coefficient between 60-90%. These studies imply that high cognitive functions of human observation are not necessary for explaining the collective pedestrian movement. The critical question here is why the random movement of agents based on the visible layout of the environment can represent the natural flow of pedestrian movement? Why the method works where at first glance, it seems to be counter-intuitive and irrational? To address these question the following section elaborates on the "social logic of space" (Hillier & Hanson, 1984), and the configurational theory of socio-spatial space.

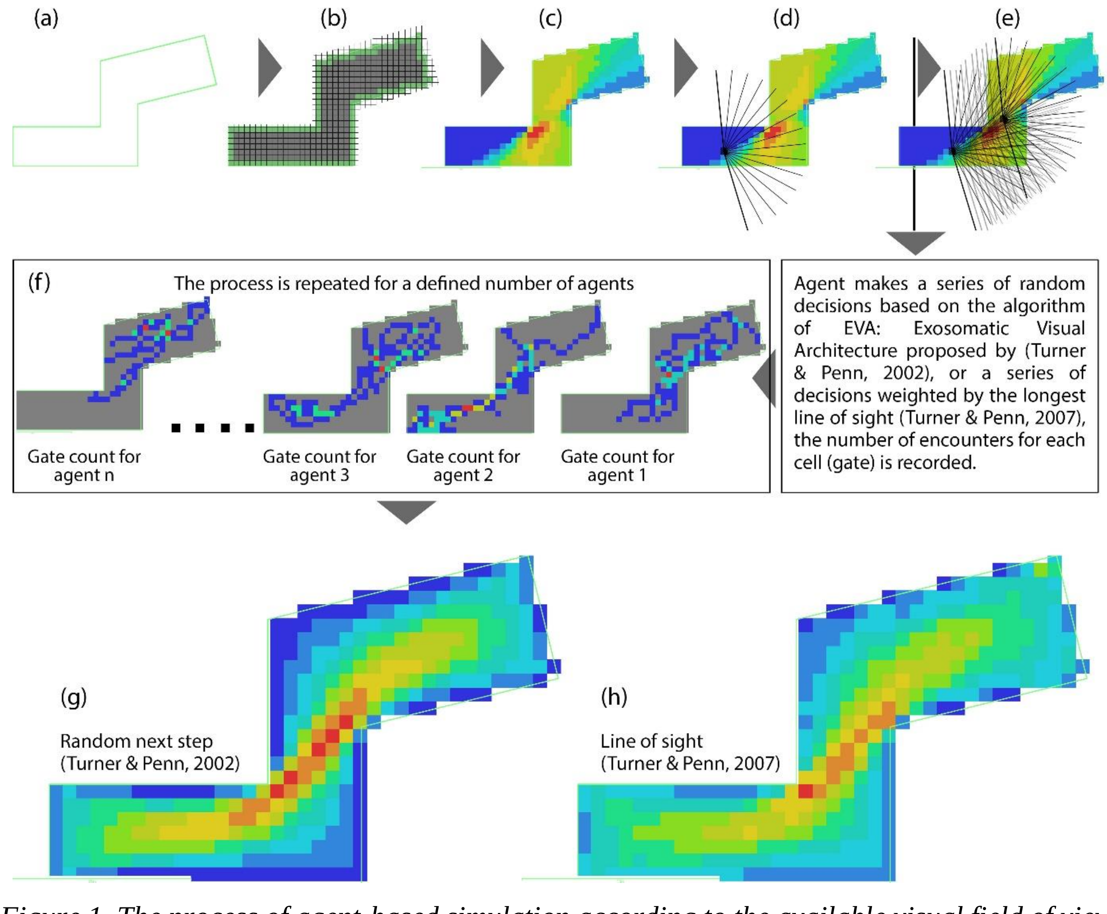


Figure 1. The process of agent-based simulation according to the available visual field of view, based on (Turner & Penn, 2002)

3. Space Syntax and Natural Movement

Urban design is a process of decision making that forms connections between people and places. Accordingly, the methodological approach for designing spaces must make a link between the spatial dimension of society and the social properties of physical forms (Karimi, 2012). This fundamental connection is the bases of space syntax method that tries to prove a tangible analytical reading of the complex socio-spatial forms of human life on the surface of the earth. Space syntax a way of looking, reading, understanding the city (or architecture) as a whole (Netto, 2016).

Space syntax is a configurational theory of socio-spatial behaviours that explores the possibilities in peoples' movements through the elemental spatial network. The spatial network is formed with an inherent "social logic" (Hillier & Hanson, 1984). Peoples' movements and spatial properties of space are connected (Hillier, 1996; Hillier, 2012). The possibility of people's presence in urban spaces is closely related with how those spaces were formed, simultaneously, the flow of people shapes the spatial grid and the spatial grid shows how people move within it. Therefore, in line with the aim of this study, space syntax offers a rich framework for evaluating socio-spatial interactions because it argues that there is a mutual relationship between how those interactions and urban spaces form and reform together.

At its core, space syntax advocates two fundamental propositions. First, space is not a mere background to human activities, it is rather a semi-social entity that co-evolves with those activities. Hence, the logic of human movement is an intrinsic aspect of the built environment (Hillier & Vaughan, 2007). The configurational geometry of the built environment is based on how people pensive and move through and to different spaces. According to Hillier (1999), people choose their paths to either minimize the necessary effort for their commute or to maximize the efficiency of it. Second, manmade spaces work in relation to each other and cannot be understood in isolation. The intricate connections among all spaces in a network are critical in how they function individually and as a whole. The most basic spaces of a house or the complex structure of a city can be represented as a network of potential movements, connections, and choices. Each component of the network has a certain function and simultaneously works with all other components of the network, this approach provides a configurational reading of city network as a whole (Karimi, 2012).

The space syntax analysis shows the effectiveness of destinations and in-between spaces of a network. This paper does not go deep into why space syntax works in predicting the collective movement of people as it is well represented throughout the space syntax literature (see Karimi, 2012). However, it is important in addressing the logic of agent-based modelling. An overall review of the literature shows the high predictability of human movement via space syntax centrality measures (Sharmin & Kamruzzaman, 2018). A study by Jiang (2009) shows that almost 60% of all movements in urban spaces can be explained by the structure of the network through space syntax measurements. Accordingly, the visibility base agent simulation makes the proposition that if the network possesses an inherent social quality then randomly moving agents in the field of visual affordance would eventually travel more through the most integrated paths.

3.1 Addressing the Land-use through Space Syntax

The relationship between land-use and space syntax has been the centre of two debates. Ratti (2004) argued that the absence of land-use in the analysis is one of the main inconsistencies of the space syntax method. Although only the changes in configurational geometry of space affect the results of the analysis, the definition and evolution process of those configurational elements bares critical significant. Hillier and Penn (2004) argue that the intrinsic social qualities that form urban spaces shape the distribution of land-use. In line with many other studies (Namely: Hillier, 2012; Kim & Sohn, 2002; Penn & Turner, 2004). We consider the land-use as a built-in function of evolving accessibility throughout the urban network. This paper implements the land-use into the analysis by providing access into the building at the ground floor of the network when movement is possible. Hillier (1999) suggests this technique the adding destinations into the analysis would weigh the analysis by the active land-use. Accordingly, all the active shops, cafes, restaurants were accessible by the agents during the simulation. The size of doors and the possibility of moving into the shops were carefully implemented into the model. This action makes a significant change in agents' patterns of movements by introducing the active ground floor plains of affordance as active players in the analysis processes (Figure 2). It seems that including more destinations provides the possibility of detours and sideways movements for the agents similar to how it affects the actual pedestrian movement. Furthermore, the implementation of geo-tagged Twitter data in this study explores the possibility of increasing the impact of active land-use (points of interest) through the perspective of social media. García-Palomares, Salas-Olmedo, Moya-Gómez, Condeço-Melhorado, and Gutiérrez (2018) show the applicability of Twitter data in reading urban land-use dynamic.

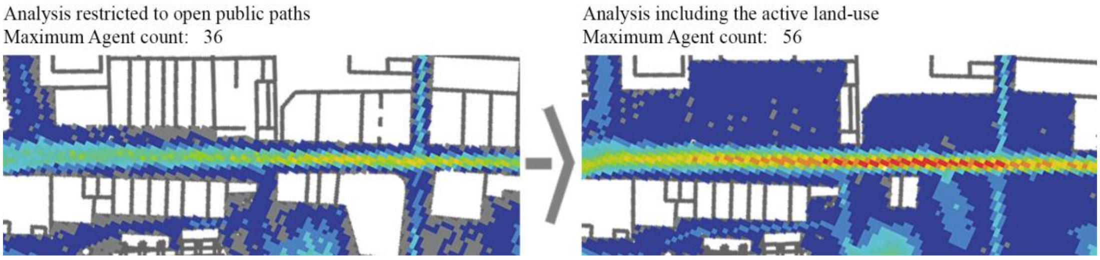


Figure 2. Improving the agent-based analysis by integration of the ground floor active land-use

4. The Emergence of Social Media into the Everyday Life of the City

One of the main contributions of this study to the main body of literature is to explore the possibility of improving the outcome of agent-based modelling with social media data that represents the new type of interaction between people and city spaces. This new form of data is the side product of the integration of social media into the everyday life of the city. The new sources of data are becoming mainstream in contemporary research, mobile devices with their convenient internal camera and connection to the internet are now a part of the framework of human life. Furthermore, mobile devices' built-in Global Positioning System (GPS) provides an unprecedented opportunity that connects the content produced by people to an actual point in urban space. Accordingly, it could be argued that the implementation of this new data is essential in understanding contemporary cities and how they function. On the other hand, the sheer volume of the data when compared to traditional surveys could potentially increase the validity of analytical urban approaches. Lazer et al. (2009) argue that our increasing capacity to collect and analyse this data is providing insight with unprecedented depth and detail in all the sciences.

This paper uses Twitter as the source of geographically tagged data as a testament to peoples interaction with the spatial network of the city. Twitter is a public social media platform with short content and additional information (if allowed by the user) to be extracted. Similar to the agent-based approach, the random tweets might seem unrelated as individual points in space, but the accumulation of these points tell a story about urban hotspots, and the intensity of active interaction. Implementation of geo-tagged Twitter data into urban research might unfold hidden socio-spatial dimensions in cities (Arribas-Bel, 2014; Shelton, Poorthuis, & Zook, 2015). Analytical methods using any type of big data (geo-tagged tweets here) must clearly address the biases, varying degrees of accuracy, and the noise that the data brings to the research (Shaw, Tsou, & Ye, 2016). Clearly, the users of Twitter do not represent the entire society and this target group might be subject to social, economic, or age biases (Lloyd & Cheshire, 2017). Currently, the users of Twitter are not a homogenous sample of the population, and the over/under presentation of certain groups must be addressed according to the objective of the research (Steiger, Westerholt, Resch, & Zipf, 2015). Many studies have shown the inherent sampling bias of the Twitter data sets, for instance, García-Palomares et al. (2018) show that people without university education are under-represented in the data. Other studies indicate the existence of biases related to age, gender, ethnicity, and geographical location (Hecht & Stephens, 2014; Mislove, Lehmann, Ahn, Onnela, & Rosenquist, 2011). Furthermore, only a small fraction of all tweets (1-3%) include geo-tag information (Kumar, Morstatter, & Liu, 2014). It could be argued that even the geo-tagged tweets which are often used for spatial analysis might not be an unbiased representation of all Twitter users. Nevertheless, Mislove et al. (2011) argue that these biases are slowly fading over time. As mobile technology is becoming a part of everyday life and as new generations are being born and raised within these frameworks, the biases are becoming less dominant. The current study acknowledges these shortcomings, but many studies support the idea that Twitter is a valuable source for understanding urban dynamics, collective human motilities, land-use, and patterns of behaviour in urban contexts (Arribas-Bel, 2014; García-Palomares et al., 2018; Shelton et al., 2015; Steiger et al., 2015).

5. Case Study: The Walled City of Famagusta

The study was conducted in the walled city of Famagusta located at the eastern coast of Cyprus. The walled city has a compelling history and its urban tissue has been formed to support a strong internal structure that can be protected by a walls-moat system. Due to its fortifications, the walled city has limited access to the surrounding urban network and it is home to numerous historic landmarks and cultural spaces. The area of the study was limited to the central part of the walled city which is home to a variety of public activities. This area includes the most dominant urban public space in front of the "Cathedral of Saint Nicholas": currently known as "Lala Mustafa Pasha Mosque" (Figure 3). The movement of cars in the selected area is limited and it offers a mostly pedestrian-friendly environment that matches the parameters of the agent-based modelling. Having the entire historic city in a small contained border helped for conducting a through agent-based analysis which is often restricted by area; it enabled the study to see the entire city as a whole, and simultaneously, the possibility for a closer detailed survey.

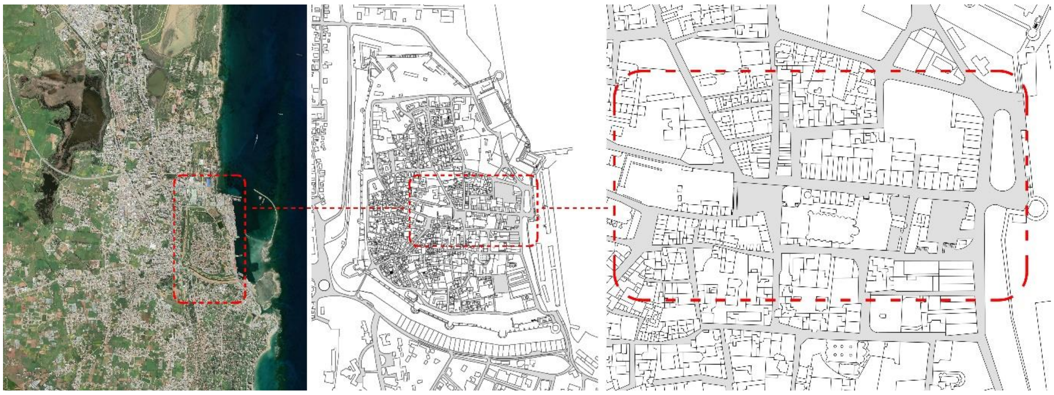


Figure 3. Left: The city of Famagusta (Google, 2019), middle: the walled city, right: the limits of the study.

The data was collected in 3 phases: first within the selected boundary of the case study, the number of pedestrians was counted for each segment. For this, the map was broken down to 72 segments (affordances). The number of people passing by each segment was counted for a 10minute window during a weekday. All segments were observed between 3-5 O'clock. The observation was repeated the following day to control for anomalies and outliers. The rounded-up average of the pedestrian count for each segment was recorded for each segment (Figure 4).

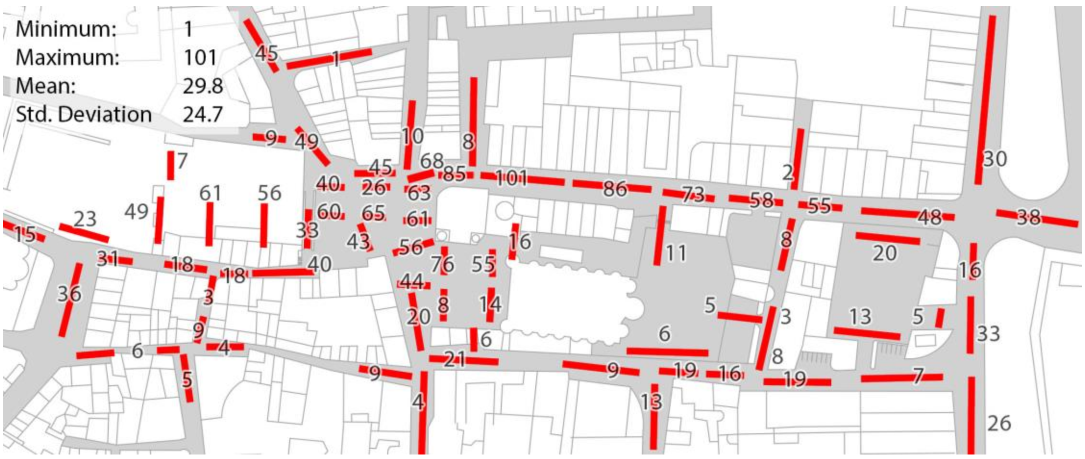


Figure 4.The result of the pedestrian count for 72 segments within the border of the case study.

Second, the agent-based analysis was performed. The analysis was done using DepthmapX developed at UCL university for space syntax analysis (Varoudis, 2012). Depthmap is a "multi-platform spatial network analysis software"[1] capable of performing a variety of spatial analysis supported by the configurational theories of space syntax. Initially, the VGA map was produced for the entire boundary of the walled city. It must be mentioned that although the boundary of the case-study is limited, both VGA and agent-based were performed for the extent of the entire area to provide a smooth and realistic representation of how people move within the network of spaces. The limitation was also set due to the software limitation for producing VGA map; the definable number of cells is limited. Accordingly, the dimension of cells was increased to 1.5m so that the entire area can be considered. All visual obstacles such as trees, thick bushes, fences were carefully taken into account. The VGA connectivity map illustrates the central public plaza as the most visually integrated section of the walled city, but a quick comparison with the number of observed pedestrian suggests that it does not have the highest pedestrian traffic. This is often caused by the distribution of active land-use which is denser around move-through streets. The agent-based simulation was conducted (Figure 5), the parameters of the simulation include:100 agents according to the maximum number of the observed pedestrian count, 5000 random steps, and the field of view was set to 170 degrees (15 bins). The obvious difference between VGA and agent base here is the shift of intensity toward the connecting streets because the agents are not looking for a final destination. The large volume of space in the main plaza leads to the dispersion of virtual agents. This is similar to the observation count of the pedestrian. The highest count of agents was assigned to each segment.

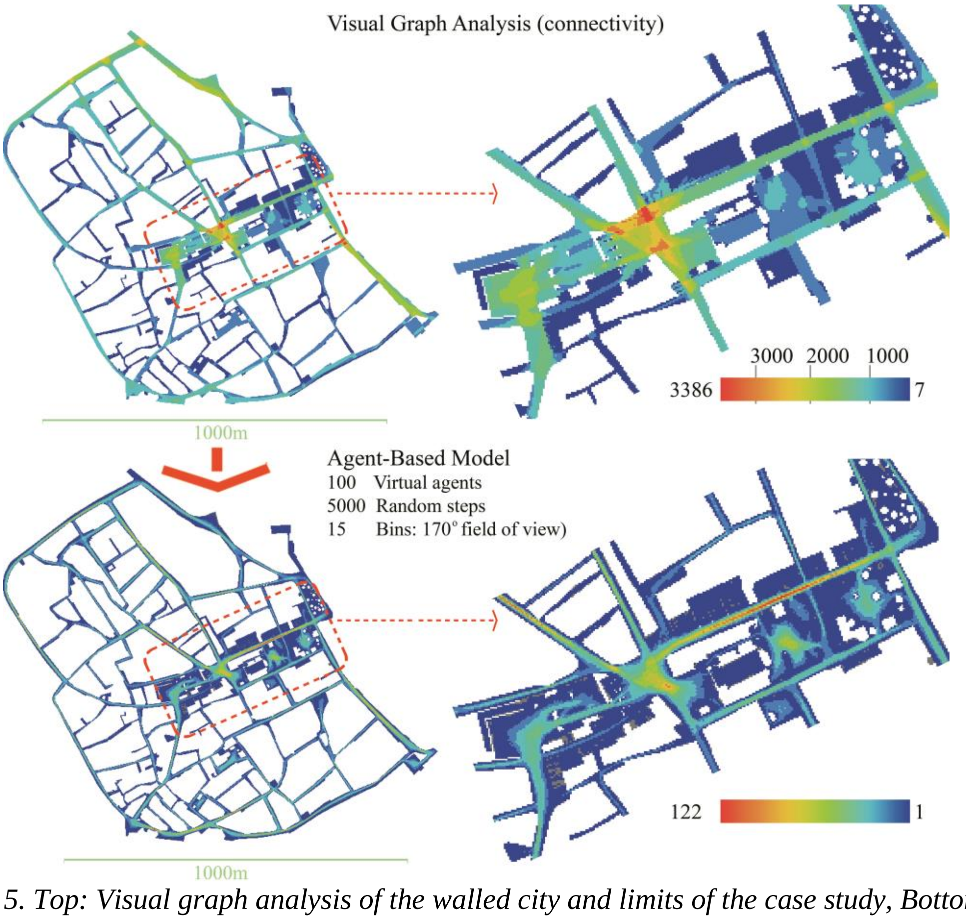


Figure 5. Top: Visual graph analysis of the walled city and limits of the case study, Bottom: the agent-based simulation.

Third, the Twitter data was collected using NodeXL application (Hansen, Shneiderman, & Smith, 2010). The tweets were collected using the inclusion of relevant metadata such as "Famagusta", "walled

[1] https://www.ucl.ac.uk/bartlett/architecture/research/space-syntax/depthmapx

city", "Cathedral of Saint Nicholas", "Lala Mustafa Pasha Mosque", "sea gate", and "Namik Kemal square". Twitter data must be used with caution, the nature of data s accidental and includes instances of irrelevant information, for instance, commercial tweets, tweets from people working at a certain place. Therefore, the processes of filtering, cleaning and sorting are necessary to make sense of the data (Iranmanesh & Atun, 2018; Lansley & Longley, 2016). Furthermore, only around 2% of all tweets include volunteer geo-tag metadata. In this case, more than 20000 tweets were collected initially, the majority of them were outside the limits of the study, among these tweets only 1683 tweets were located inside the limits of the study, included intact geo-tagged data, and met the filtering requirements set for this study. The majority of the final tweets are linked with cafes, restaurants, the main public plaza, and historic checkpoints. Figure 6 shows an interesting phenomenon, in the public plaza the majority of tweets are located in distance with the main façade of the cathedral, this zone is the best place to observe and to take pictures of the building.

Figure 6. The filtered geo-tagged Twitter data superimposed on the map.

Conducting a simple regression using the observation data as the independent variable shows that 59% of all movements can be explained by the agent simulation (

Table *1*). The results confirm the findings of the previews studies (Aknar & Atun, 2017; Jiang & Jia, 2011; Koutsolampros & Varoudis, 2017; Penn & Turner, 2002; Turner & Penn, 2002). It could be argued that the bottom-up approach of constructing models based on the configurational aspects of space can provide a reliable illustration of pedestrian behaviour. This finding also indicates that increasing the cell size to 1.5m is applicable in predicting pedestrian movements. Furthermore, using geo-tagged Twitter data shows a slightly different picture. The Twitter data cannot be predicted by the agent model at the same level (R^2=0.20), this dissimilarity could be explained by the nature of Twitter data which is more closely related to land-use and does not work well with constantly moving agents. The majority of tweets, in this case, are coming from destinations, not move-through spaces, this can be shown by the correlation coefficient between tweet count and pedestrian count (R^2=0.31). although the correlation between the two variable is significant, it is not as strong as the predictability of pedestrian count via agent count. Building upon this idea, conducting a multiple regression using both agent count and tweet count shows 10% improvement over the simple regression (R^2=0.69). This outcome confirms that the spatial nature of two data types is different.

Furthermore, Inclusion of Visual connectivity does not improve the statistical model because the agent count is built upon the VGA and it is superior for predicting pedestrian movement. The results were further controlled by the alternative model suggested by Turner and Penn (2007) based on the longest line of sight. The statistical model shows a slightly lower correlation coefficient (Figure 7: R^2=0.45).

Table 1. Regression model for exploring the predictability of pedestrian movement vis agent-based and Twitter data.

	Regression	Independent variable	R^2	Sig.	Collinearity Diagnostics VIF
Dependent Variable: Pedestrian Count	Simple linear regression	Agent Count	0.59	0.000	-
		Twitter Count	0.31	0.000	-
		Visual connectivity	0.36	0.000	-
	multiple regression (enter)	Agent Count Twitter Count	0.69	0.000	1.21
		Agent Count Visual connectivity	0.60	0.000	1.52
		Agent Count Visual connectivity Twitter Count	0.70	0.000	1.61 1.66 1.31

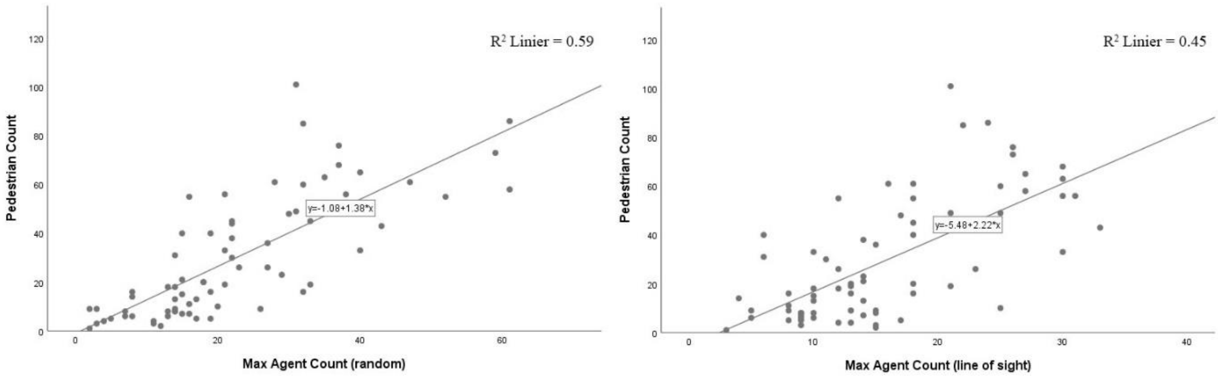


Figure 7. Left: the scatter plot of random next step agent-base against the pedestrian count, right: the line of sight agent-based model against pedestrian count.

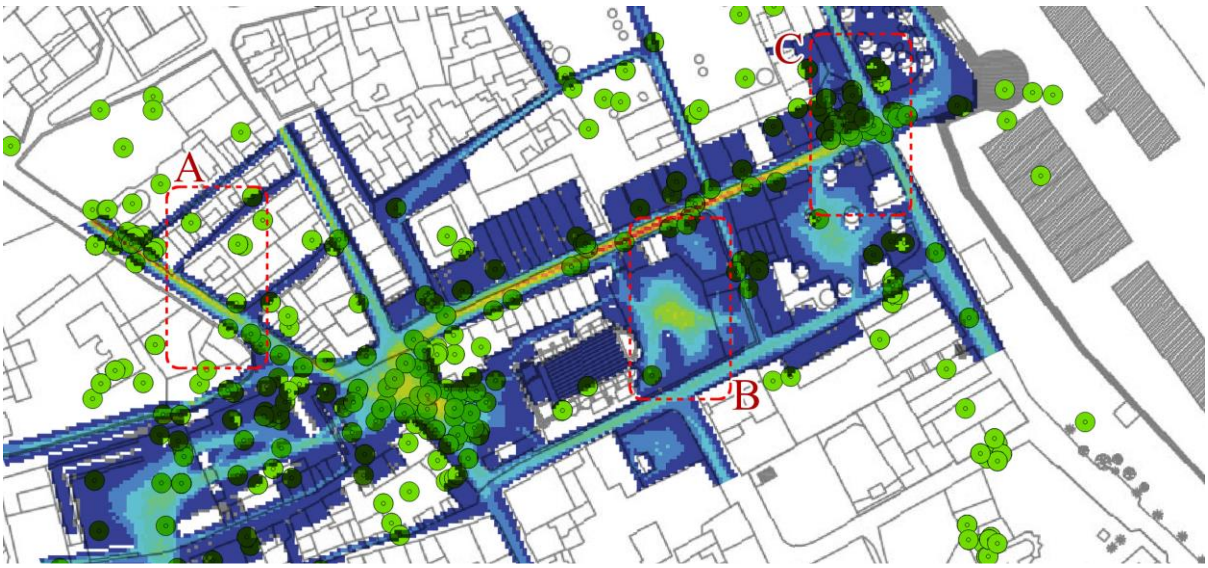


Figure 8. Spatial anomalies

Going back to the two basic propositions of space syntax, it is clear that the central spaces of the grid are also most visited by virtual and real agents! Tourists randomly around find themselves in these spaces. The land-use can affect the movement but it is the movement that eventually defines the land-use. This method can be implemented in problem diagnostics/solving phases of urban design. There are spaces that show potential in terms of affordance but fail to show significant pedestrian movement, the potentials of these spaces must be utilised in urban land-use development (Figure 8: A). Figure 8:B shows the space behind the cathedral, the agents seem to find it easily but the pedestrian count is low, this might be caused by the limited points of access to the space, it seems that some agents are being trapped inside and since it is a large space they survive and leave a mark; this space can be used for exactly such activities!, exhibitions, workshops, and NGOs. Figure 8:C shows a space with the highest number of tweets, it is connected to a famous pastry shop and also one of the best places to look back and snap a photo, however, the car traffic that cuts through space undermines its potential for pedestrian movement.

6. Conclusion

This paper undertakes the predictability of pedestrian movement through visibility base agent simulation and tries to improve the result by integrating new sources of geotagged social media data representing emerging ICT. The agent-based modelling is built on the bottom up idea that geometrical layout of the field of vision/movement is the most influential in how people move through space. Accordingly, virtual agents are making random steps on bases of available ground, and the accumulation of encounters with segments of space creates an intensity map that shows a strong correlation with pedestrian behaviour. Our findings confirm and improve upon the existing literature on the field by the addition of geo-tagged tweets into the regression model. The result shows 10% improvements over the agent-based model. The geo-tagged tweets bring some aspects of the active land-use into the equation, they represent urban hotspots and points of interests. It could be argued that the improvement is caused by introducing destination motivated movements upon the existing random through-movements. Twitter was used in this study as a representation of people's digital footprint. The mobile devices and social media are becoming inseparable features of everyday life on contemporary urban spaces, so the research must take the emerging field of communication into account. The results are interpreted through space syntax configurational theories, and answers the question that why random movements can make sense of built environment? cities have been, and are being constantly formed by people through a collective logic that is fabricated into the essence of space. Furthermore, future studies could focus on the effects of biases in the Twitter user profile by providing more detailed content and user classifications.

References

Aknar, M., & Atun, R. A. (2017). Predicting movement in architectural space. *Architectural Science Review, 60*(1), 78-95.

Arribas-Bel, D. (2014). Accidental, open and everywhere: Emerging data sources for the understanding of cities. *Applied Geography, 49*, 45-53.

depthmapX: visual and spatial network analysis software. Retrieved from https://www.ucl.ac.uk/bartlett/architecture/research/space-syntax/depthmapx

García-Palomares, J. C., Salas-Olmedo, M. H., Moya-Gómez, B., Condeço-Melhorado, A., & Gutiérrez, J. (2018). City dynamics through Twitter: Relationships between land use and spatiotemporal demographics. *Cities, 72*, 310-319.

Gibson, J. J. (1979). The ecological approach to visual perception.

Gibson, J. J. (2014). *The ecological approach to visual perception: classic edition*: Psychology Press.

Hansen, D., Shneiderman, B., & Smith, M. A. (2010). *Analyzing social media networks with NodeXL: Insights from a connected world*: Morgan Kaufmann.

Hecht, B., & Stephens, M. (2014). *A tale of cities: Urban biases in volunteered geographic information.* Paper presented at the Eighth International AAAI Conference on Weblogs and Social Media.

Hillier, B. (1996). *Space is the Machine: A Configurational Theory of Architecture*. Cambridge: Press Syndicate.

Hillier, B. (1999). The hidden geometry of deformed grids: or, why space syntax works, when it looks as though it shouldn't. *Environment and planning B: Planning and Design, 26*(2), 169-191.

Hillier, B. (2012). Studying Cities to Learn about Minds: Some Possible Implications of Space Syntax for Spatial Cognition. *Environment and planning B: Planning and Design, 39*(1), 12-32. doi:doi:10.1068/b34047t

Hillier, B., & Hanson, J. (1984). *The Social Logic of Space*. Cambridge Cambridge University Press.

Hillier, B., & Penn, A. (2004). Rejoinder to carlo ratti. *Environment and planning B: Planning and Design, 31*(4), 501-511.

Hillier, B., & Vaughan, L. (2007). The city as one thing. *Progress in Planning, 67*(3), 205-230.

Iranmanesh, A., & Atun, R. A. (2018). Exploring the spatial distribution of geo-tagged Twitter feeds via street-centrality measures. *Urban Design International*. doi:10.1057/s41289-018-0073-0

Jiang, B. (2009). Ranking spaces for predicting human movement in an urban environment. *International Journal of Geographical Information Science, 23*(7), 823-837.

Jiang, B., & Jia, T. (2011). Agent-based simulation of human movement shaped by the underlying street structure. *International Journal of Geographical Information Science, 25*(1), 51-64.

Karimi, K. (2012). A configurational approach to analytical urban design:'Space syntax'methodology. *Urban Design International, 17*(4), 297-318.

Kim, H.-K., & Sohn, D. W. (2002). An analysis of the relationship between land use density of office buildings and urban street configuration: Case studies of two areas in Seoul by space syntax analysis. *Cities, 19*(6), 409-418.

Koutsolampros, P., & Varoudis, T. (2017). *Assisted agent-based simulations: fusing non-player character movement with space syntax.* Paper presented at the Proceedings of the 11th International Space Syntax Symposium.

Kumar, S., Morstatter, F., & Liu, H. (2014). *Twitter data analytics*: Springer.

Lansley, G., & Longley, P. A. (2016). The geography of Twitter topics in London. *Computers, Environment and Urban Systems, 58*, 85-96.

Lazer, D., Pentland, A. S., Adamic, L., Aral, S., Barabasi, A. L., Brewer, D., . . . Gutmann, M. (2009). Life in the network: the coming age of computational social science. *Science (New York, NY), 323*(5915), 721.

Lloyd, A., & Cheshire, J. (2017). Deriving retail centre locations and catchments from geo-tagged Twitter data. *Computers, Environment and Urban Systems, 61*, 108-118.

Mislove, A., Lehmann, S., Ahn, Y.-Y., Onnela, J.-P., & Rosenquist, J. N. (2011). *Understanding the demographics of twitter users.* Paper presented at the Fifth international AAAI conference on weblogs and social media.

Netto, V. M. (2016). ‘What is space syntax not?’Reflections on space syntax as sociospatial theory. *Urban Design International, 21*(1), 25-40.

Norman, D. A. (1999). Affordance, conventions, and design. *interactions, 6*(3), 38-43.

Penn, A., & Turner, A. (2002). Space syntax based agent simulation: Springer-Verlag.

Penn, A., & Turner, A. (2004). Movement-generated land-use agglomeration: simulation experiments on the drivers of fine-scale land-use patterning. *Urban Design International, 9*(2), 81-96.

Ratti, C. (2004). Space syntax: some inconsistencies. *Environment and planning B: Planning and Design, 31*(4), 487-499.

Sharmin, S., & Kamruzzaman, M. (2018). Meta-analysis of the relationships between space syntax measures and pedestrian movement. *Transport Reviews, 38*(4), 524-550.

Shaw, S.-L., Tsou, M.-H., & Ye, X. (2016). Human dynamics in the mobile and big data era. *International Journal of Geographical Information Science, 30*(9), 1687-1693.

Shelton, T., Poorthuis, A., & Zook, M. (2015). Social media and the city: Rethinking urban socio-spatial inequality using user-generated geographic information. *Landscape and urban planning, 142,* 198-211.

Steiger, E., Westerholt, R., Resch, B., & Zipf, A. (2015). Twitter as an indicator for whereabouts of people? Correlating Twitter with UK census data. *Computers, Environment and Urban Systems, 54*, 255-265.

Turner, A., Doxa, M., O'sullivan, D., & Penn, A. (2001). From isovists to visibility graphs: a methodology for the analysis of architectural space. *Environment and planning B: Planning and Design, 28*(1), 103-121.

Turner, A., & Penn, A. (2002). Encoding natural movement as an agent-based system: an investigation into human pedestrian behaviour in the built environment. *Environment and planning B: Planning and Design, 29*(4), 473-490.

Turner, A., & Penn, A. (2007). Evolving direct perception models of human behavior in building systems *Pedestrian and Evacuation Dynamics 2005* (pp. 411-422): Springer.

Varoudis, T. (2012). DepthmapX multi-platform spatial network analysis software. *Version 0.30 OpenSource, http://varoudis. github. io/depthmapX.*

Northumbria University NEWCASTLE

ISBN (Print) 9781861354877

ISBN (eBook) 9781861354860

Layout Editor :
Moslem Sheikhkhoshkar